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A Technology Assessment of

LASER ULTRASONICS

By

James Wagner and James Spicer
The Johns Hopkins University

Prepared for

NTIAC

Nondestructive Testing Information Analysis Center
A DoD Information Analysis Center Sponsored by the
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PREFACE

This Technology Assessment was prepared by Profs. James Wagner and James Spicer from The Johns Hopkins University, Baltimore, MD, under a subcontract from NTIAC. Prof. Wagner is now Dean of Engineering at Case Western Reserve University in Cleveland, OH. Partial support for preparation of the Technology Assessment was provided through an NTIAC Subscription Plan by Dr. Curt Fiedler, Air Force Research Laboratory, Wright Patterson AFB, OH.

Included in the Appendix is the edited transcription of a Panel Discussion on Laser Ultrasonics which took place June 17, 1997, as part of the Eighth International Symposium on Nondestructive Characterization of Materials in Boulder, CO. The Panel Discussion was moderated by Prof. Spicer and Dr. Fiedler.

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A Technology Assessment of Laser Ultrasonics

1.0 Introduction

The terms Laser Ultrasonics (LU) and Laser-based Ultrasonics (LBU) relate to a range of testing and measurement configurations that employ lasers both to generate and to detect ultrasonic signals at the surface of opaque materials or in the bulk of transparent media. The ability to perform ultrasonic measurements in a remote and non-contacting manner using laser methods has produced significant interest in this measurement technology from a range of users. Numerous demonstrations of the technology in university, government and industrial laboratories have shown the flexibility and promise of laser ultrasonics and have pointed to its potential limitations. Unlike conventional ultrasonic methods which have experienced broad use in a variety of applications (industrial quality control, materials process sensing, medical imaging, infrastructure inspection), laser based methods have been used primarily in research programs and in technology demonstrations. Unfortunately, even with successful demonstrations, the use of laser ultrasonics outside the research environment has not occurred. In part, the movement of this technology to broader application has been limited by the nature of laser ultrasonic technology development.

First, the most significant demonstrations of laser ultrasonic technology have occurred in a few industrial and government laboratories where significant external funding (combined perhaps with internal funding) for the development of laser ultrasonic methods has been received for multi-year terms. The sustained development of the technology in these laboratories has produced impressive results for laser ultrasonic methods. Unfortunately and significantly, by comparison, little funding has been provided to universities to investigate exploratory research into advancing the state-of-the-art; consequently, the cadre of knowledgeable laser ultrasonics researchers is fragmented and restricted such that a critical mass of researchers rarely assembles for discussion of critical issues to the technology. Fortunately, as part of this technology assessment, a panel of laser ultrasonics practitioners from around the world were gathered at the Eighth International Symposium on Nondestructive Characterization held in Boulder, Colorado (June, 1997) to discuss the critical issues surrounding the future development of laser ultrasonic technologies. A transcription of the comments of the panel is included as an appendix to this assessment. However, to interpret and understand the comments made by these respected workers, background information on the past development of the technology must be given.

Secondly, the involved nature of laser light interactions with materials and a lack of understanding of the influences that these interactions have on laser

ultrasound has limited the deployment of laser ultrasonic sensing technologies. The number of parameters that affect laser/material interactions is significant such that when these parameters are linked to ultrasound generation and detection, it is clear that the laser ultrasonic process is not trivial in its description. The purpose of this technology assessment is to: i) briefly review the essential aspects of laser ultrasonic methods highlighting characteristics which make it attractive for ultrasonic testing ii) summarize the areas in which the capabilities of laser ultrasonics have been demonstrated and iii) recommend directions for technology development given the current understanding of the technology. The first two parts of this assessment give context to the third part and to aid the interpretation of the comments made by the expert panel on laser ultrasonics.

2.0 Technology Description

As is the case for conventional ultrasonic methods, laser ultrasonic systems use an ultrasonic transmitter and receiver to, respectively, generate and detect ultrasound that is propagated through the material. Owing to the widespread use of traditional methods, immediate (and sometimes unfortunate) parallels are drawn between laser ultrasonic methods and conventional piezoelectric methods for generation and detection of ultrasound in materials. However, the transduction mechanisms themselves differ significantly between the two techniques. For example, transduction of electrical energy to ultrasonic energy and back again is performed in a conventional transducer by the same piezoelectric phenomenon. In laser based methods, it is the material itself which transduces optical energy first to thermal and then ultimately to elastic energy which propagates as ultrasound in the material. For reception of the ultrasonic energy, a second laser system directly detects the small fluctuations in surface position produced by the ultrasonic displacements.

The fundamental differences in transduction between conventional ultrasonics and laser-based ultrasonics give rise to important advantages and disadvantages in the application of laser-based methods relative to conventional counterparts. For example, since transduction of ultrasound takes place at the surface or within the bulk of the test material itself rather than within a piezoelectric material, there is no requirement for a mechanical coupling to a transducer external to the material. In other words, whereas piezoelectric transducers require solid bonding, fluid coupling, or even air coupling, laser-based methods require only that optical access to the material exists and that the material absorb light from the laser source. Consequently, laser methods permit noncontact and remote generation of ultrasound in a test material. Similarly, the detection of ultrasonic disturbances using a laser requires no mechanical couplant and also permits noncontact and remote measurement. Another less intuitive consequence of the material serving as the transducer, converting light to sound, is the fact that the radiation pattern of the sound in the material always is referenced to the materials surface normal. For a point of laser light focused on the surface, the

direction of sound propagation from that surface will be independent of the angle of incidence for the laser beam. This fact significantly relaxes the constraints on a robotic scanning system which might be used to perform ultrasonic testing on a material with irregular surface geometry. With water squirter coupling methods (used quite commonly to inspect large panels of aircraft structures) there is a need for the squirter itself to be positioned always perpendicular to the material surface. Ultrasound generated by the laser will always propagate relative to the perpendicular of the surface without the need to maintain perpendicular incidence of the laser beam. Unfortunately, the independence from angular incidence for generation of sound via laser does not obtain fully for laser detection of ultrasound. Somewhat more angular constraint is required in detection since most optical detection methods are primarily sensitive to displacements along the axis of the detecting laser beam. Thus, for a displacement which might occur strictly normal to the test surface, sensitivity to the detection of that displacement would fall off as the cosine of the angle between the detecting beam and the surface normal.

Given these properties associated with laser methods for generation and detection of ultrasound, other potential advantages of the methodology become clear. For example, since there is no contact with the surface of the material being tested, ultrasonic inspection of materials in hostile environments where elevated temperatures or hazardous conditions may prevail or of very delicate, thin-film materials may be accomplished using laser ultrasonic methods. The "footprint" on the surface of the material over which sound is generated or detection takes place can be shaped arbitrarily from a point of light to a large pattern which can be used to direct or focus ultrasonic energy generated by a laser. Additionally, since the material itself is performing a transduction function, the acoustic mismatch between the heated region and the rest of the material is small such that no mechanical resonance associated with the transduction mechanism occurs. Consequently, without resonance, laser generation and detection of ultrasound can be performed with extremely broad detection bandwidths. These bandwidths ensure high fidelity recording of the ultrasonic displacements.

Accompanying the great promise for laser ultrasonics outlined above is a list of potential disadvantages of the technology as it currently exists relative to conventional contact ultrasonics. Cost and modest detection sensitivity are the two most frequently cited disadvantages which restrict broader application of laser-based ultrasonic methods. Consequently, these two disadvantages represent a target for the most intensive technological research and development efforts in the field. Neither issue, cost nor sensitivity, lends itself to simple analysis. Costs for laser ultrasonic systems have ranged from simple laboratory-based instruments costing under $25,000 to full-scale field implementations such as the scanning laser ultrasonic system installed by the federal government at the McClellan Air Force Base in Sacramento, California for a cost in excess of $5 million. It is interesting to note that this same range of costs defines the extremes of cost for conventional

ultrasonic systems as well. However, even low-end laser ultrasonic systems carry price tags higher than the median cost for most conventional ultrasonic testing and inspection equipment. Furthermore, costs for laser ultrasonic systems tend to fluctuate more broadly as a function of application than do their conventional piezoelectric counterparts. That laser ultrasonic systems must be engineered for each specific application is often a direct consequence of the fact that each material represents a different "transducer efficiency" which must be optimized each time the target material is changed. For example, a conventional water squirter-type scanning system for ultrasonic inspection of aircraft panels can be used to inspect aluminum skins or composite structures. Either task can be performed well with a laser ultrasonic system; however, a system designed for composite material inspection will not function well for inspection of aluminum with the converse being true as well. In spite of the relative expense of laser-based technology, it is important to consider that certain measurement tasks in manufacturing process control can be accomplished through the use of laser technology but not at all with conventional contact ultrasonics.

Material specific performance is a key component dictating the limits of sensitivity with which a particular laser ultrasonic system can perform. Once again, the reasons for this will be discussed in greater detail later, but even with the general description already given of the principles of laser ultrasonics, it should be clear that a material which is an efficient absorber and transducer of optical energy into ultrasonic energy will be able to perform measurement and inspection tasks with higher detection sensitivity. For such efficient materials, thicker specimens may be ultrasonically evaluated compared to material which, by its physical nature, is a poor transducer of optical to ultrasonic energy.

3.0 Technology Applications

In spite of cost and sensitivity issues, laser ultrasonic technology already has been able to satisfy some very important inspection and process control needs. As an inspection tool, the current state-of-the-art of the technology favors the use of laser ultrasonics not as a field portable methodology but rather as an inspection station to which structures and components can be brought for inspection. Where air, land, and sea transport equipment can be brought to central facilities for periodic maintenance, including large area ultrasonic inspection, laser-based methods have demonstrated great potential using currently existing technology. In fact, the Sacramento-based system mentioned earlier is just such a facility performing inspection of large composite components of military aircraft.

As important a role as laser ultrasonic methods may play in inspection tasks, one might expect an even greater impact from this technology as it is applied for manufacturing process control. Manufacturing costs for advanced structural materials, as well as for new electronic and photonic materials, can be extremely high even while the manufactured product quality is not well-controlled. In some

cases, product quality can be improved and costs reduced by the development and implementation of appropriate sensor technologies to provide feedback for process-control based on direct measurement of the properties of the product in the manufacturing line. Laser ultrasonics promises to provide one such measurement technology permitting non-contact and real-time updates of important physical properties of a manufactured material. For example, since ultrasonic velocity in many materials has a strong dependence on temperature, possibilities exist to use laser-based ultrasonic methods to determine the temperature of the product in-process. Numerous other examples of applications for process control are the focus of various research and development efforts around the world and will be presented later.

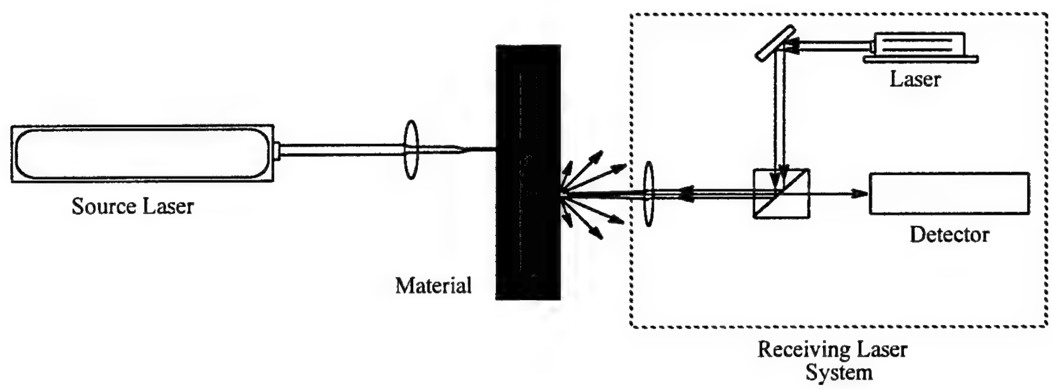

Figure 1: Generalized laser ultrasonic system showing the essential components: the source laser, the material and the receiving laser system

4.0 Background for the Technology

An understanding of the physical basis for laser-based ultrasonic measurements is assisted by considering Figure 1. Note that the figure contains only three components - a source laser, the material, and a receiving laser system. These three components are common to every laser ultrasonic system. The particular configuration illustrated here is one where sound is launched from the front surface of the material and is detected after it propagates through the material to the back surface. In general, the relative positioning of the source and the receiver points is arbitrary even permitting generation and detection from the same point if desired. By considering each of these three components, the source, the material, and the receiver separately, a basic understanding of the principles of laser ultrasonics, its performance attributes, and its limitations can be understood.

First, consider the laser source. As discussed in the introduction, the laser is not the source of ultrasound but rather the source of optical energy to be transduced by the material surface into ultrasonic energy. The source laser in typical applications is a pulsed laser with pulse durations ranging from five nanoseconds to 100 nanoseconds. It is interesting to note that in very highly specialized applications such as measurement of elastic properties of extremely thin films and coatings, laser sources with picosecond pulse durations have been employed [1-4]. As the laser energy is absorbed by the target material, the mechanism of transduction to ultrasonic energy may involve contributions from both material thermoelasticity and, at higher power densities, from material ablation. Thermoelastic generation of ultrasound is the result of rapid local heating of the material giving rise to sharp thermal gradients within the material. Owing to thermal expansion of the material, local regions of high mechanical strain can accompany the high thermal gradients. These strain fields then may evolve into any of several ultrasonic modes that propagate throughout the material. For laser sources with pulse durations of ~ 10 ns, these ultrasonic modes contain significant ultrasonic energy with frequency content up to ~ 50 MHz. The ultrasonic energy is broadband for all of the excited ultrasonic modes. A schematic of the modes in isotropic materials is shown in Figure 2. At low power densities where relatively small temperature rises are observed, this thermoelastic transduction mechanism can truly be nondestructive. One can understand that the optical absorption and the thermal expansion characteristics of the material will be two important factors determining the transduction efficiency for a particular material. Additionally, however, properties such as the depth of optical penetration and the condition of the material surface can also have strong effects on the nature of the ultrasonic energy transduced from the optical laser pulse. In the thermoelastic regime, the directivity of the ultrasonic energy beneath the surface of the material is a strong function of the geometry of the volume heated by the laser pulse [5]. In metals, for example, where absorption of visible or near infrared light takes place at or very near the surface of the material, the laser source gives rise in the far-field to directivity patterns for both longitudinal and shear bulk waves which trace out a hollow cone

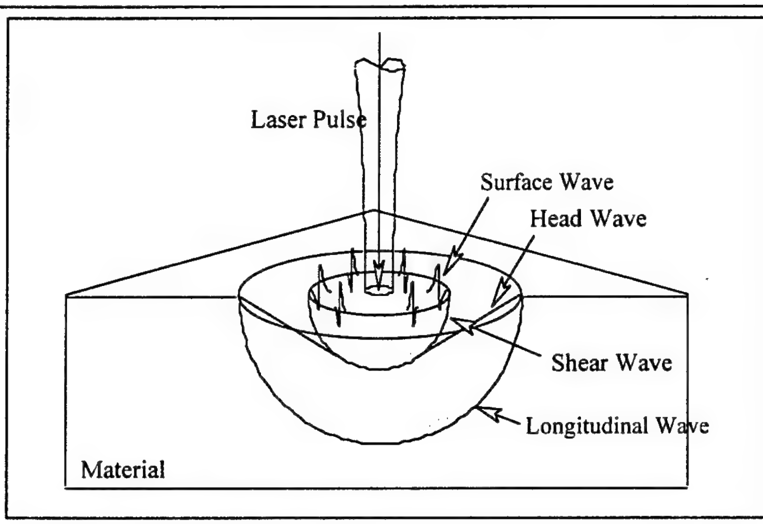

Fig 2: Schematic of the ultrasonic waves launched by the laser source. In isotropic materials, most of the acoustic source energy is coupled to the surface wave; however significant longitudinal and shear deformations occur.

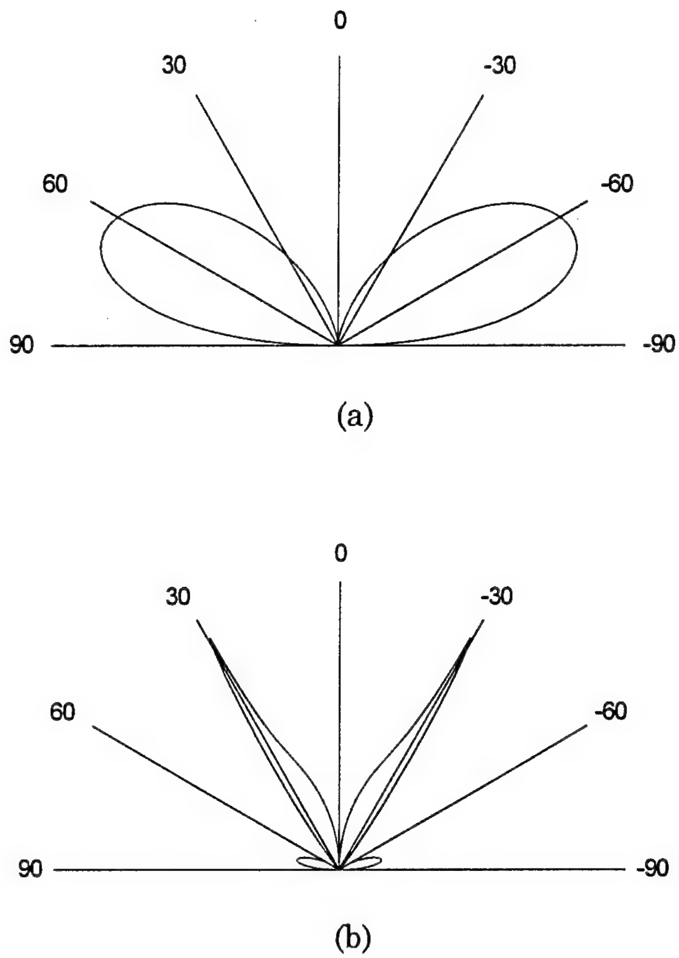

Figure 3: Ultrasonic wave amplitude directives in isotropic materials for thermoelastic generation on the surface of a half-space: a. far-field longitudinal wave directivity pattern, b.: far-field shear wave directivity pattern.

radiating from the source point (see Figure 3). For longitudinal waves, the directivity pattern can be changed profoundly by providing some sort of mechanical constraint to the surface of the material [6, 7, 8]. Such constraint can be provided by thin layers of moisture or oil through which the laser beam passes before interacting with the material. Because the surface layer provides a mass which constrains the outward expansion of the thermoelastically excited surface region, longitudinal waves now are directed most strongly on axis as illustrated in Figure 4. This same on-axis directivity pattern from a thermoelastic source is observed, also, when the laser energy is absorbed at some point beneath the surface of the target material. Deeper laser absorption occurs naturally in certain polymer and composite systems as well as in many ceramic materials. The directivity pattern is altered for extreme penetration depths, such as for CO_2 laser light absorbed in ocean water [9-12]. Directivity and wave form shape are affected by elastic anisotropy of the material [13-16]. Fortunately, these issues of waveform shape and directivity are well understood and have been modeled with good accuracy by several investigators [17, 18, 19]. In addition to bulk longitudinal and shear modes, the thermoelastic mechanism for transduction of laser energy to ultrasound can excite guided modes including surface waves and Lamb waves in plates and rod modes [20-24].

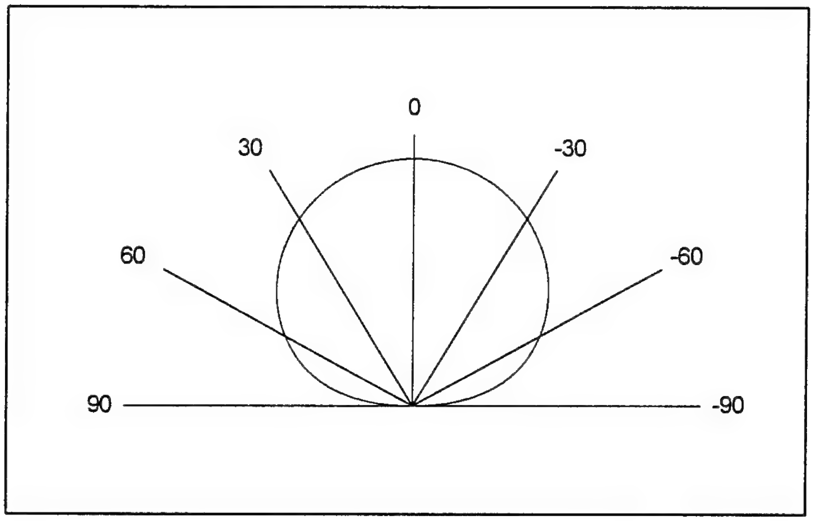

Figure 4: Longitudinal wave amplitude directivity in the far-field for a normal, point loading of an isotropic half-space. This type of directivity pattern is expected for ablation or for constrained-surface generation mechanisms.

As the optical power density delivered to the material increases, the additional heat delivered can cause a corresponding rise in temperature depending upon the heat capacity and the thermal conductivity of the material within a small range of high power densities. One may proceed first to melting and then to vaporization temperatures for the material, thus resulting in material removal through heating or ablation. Ejection of the molten material and vapor from the surface can impart a transfer of momentum at the material surface contributing to local strains. In fact, with the onset of surface damage and ablation, the contribution to the ultrasonic signal from this momentum transfer can rapidly exceed and ultimately dominate contributions to the displacements from thermoelasticity. Since material is ejected in a direction perpendicular to the surface, the directivity pattern of an ablative source for longitudinal waves is once again predominantly on-epicenter similar to that of a constrained or buried thermoelastic source. This directivity from the ablative source is observed even for materials which allow minimal optical penetration and would produce a conical directivity pattern for a thermoelastic source. The changes in directivity in metallic materials between the thermoelastic and ablative sources is accompanied by an enhancement of the amplitude of the elastic wave generated in the bulk of these materials [5]. With increasing power density beyond the onset of material ablation, the amplitude of the shear mode on-epicenter is observed to diminish. Ultimately, at extremely high power densities even the longitudinal wave amplitude decreases [25]. The reason for this drop in transduction efficiency after a dramatic increase with power density is attributed to the formation of plasma during ablation which is highly conductive and may actually shield the material from absorbing additional light from the laser pulse [26, 27, 28].

In addition to power density, other laser source parameters can have significant effects on the transduction efficiency and the nature of the ultrasonic energy generated by the laser source. Perhaps the most obvious among the selectable source parameters is the effect of laser wavelength on transduction

efficiency. For some materials, it is possible to select an optical wavelength to permit strong absorption or deep penetration depending on the desired performance of the source. In various materials, such as metals and polymers for example, strong absorption and increased penetration are achieved by employing a source wavelength in the ultraviolet regime, such as might be obtained from an eximer laser [29]. In graphite epoxy materials, both CO_2 laser wavelengths at 10.6 μm and Nd:YAG laser wavelengths at 1.06 μm have been investigated [30, 31]. The CO_2 laser light is strongly absorbed in the epoxy matrix material but provides adequate penetration to generate strong on-axis directivity of ultrasound. The Nd:YAG laser light penetrates with very little absorption in the matrix material and is absorbed strongly in the graphite reinforcing fibers, again, resulting in a buried source. Wavelength choices, also, are important in determining the mechanisms by which laser light can be delivered to the test surface. The convenience of fiber-optic delivery, for example, would be desirable for many laser ultrasonic applications. Even though the 10.6 μm output from a CO_2 laser can be effective as a source for polymer and polymer-based composites, is not efficiently delivered by existing fiberoptic technology. Consequently, alternative laser sources have been considered, including the Alexandrite laser [32].

Beyond power density and wavelength, laser pulse duration can be an important parameter to be optimized for the most efficient laser generation of ultrasound. Pulse duration can be especially important when it is desirable to operate in a nondamaging thermoelastic laser generation regime. Appropriate choices for laser pulse duration are based on a compromise between two competing phenomena within the material. The first of these phenomena is the very effect contributing to elastic wave generation which requires that a sharp thermal gradient exist within the material in order that correspondingly large elastic strain gradients be established that propagate throughout the material. It could be assumed that, in general, it would be desirable to deposit heat within the target material as rapidly as possible, and for that reason very short laser pulses should be employed. In fact, with the exception of laser ultrasonic work performed in extremely thin films, investigators routinely employ laser sources with pulse durations of only a few nanoseconds.

Competing with the desirability of providing heat during a short time period is the risk that the local temperature of the material may build so rapidly as to result in melting and ablation damage. Local temperature build-up is a function of the specific heat and the thermal conductivity of the material. From those and related materials parameters, it is possible to predict the material temperature increase as a function of laser pulse energy and pulse duration [33]. From such models, it is possible to predict the maximum amount of energy that can be delivered to a material while staying below a damage temperature threshold. For aluminum, the effects of increasing pulse width are shown in Figure 5. As is shown, substantially longer pulse widths than are associated with most Q-switched

laser outputs actually permit more energy to be coupled into material before a damage threshold is crossed. However, the high thermal conductivity of aluminum results in a point of diminishing returns with increasing pulse width. For graphite epoxy composites, the relatively low thermal diffusivity of the composite material confines the thermal energy for relatively long times and more energy that contributes to ultrasonic generation may be deposited into the composite. The practical limit for increasing pulse duration is reached when the ultrasonic frequencies generated by the laser pulse are affected/diminished by the duration of the laser pulse.

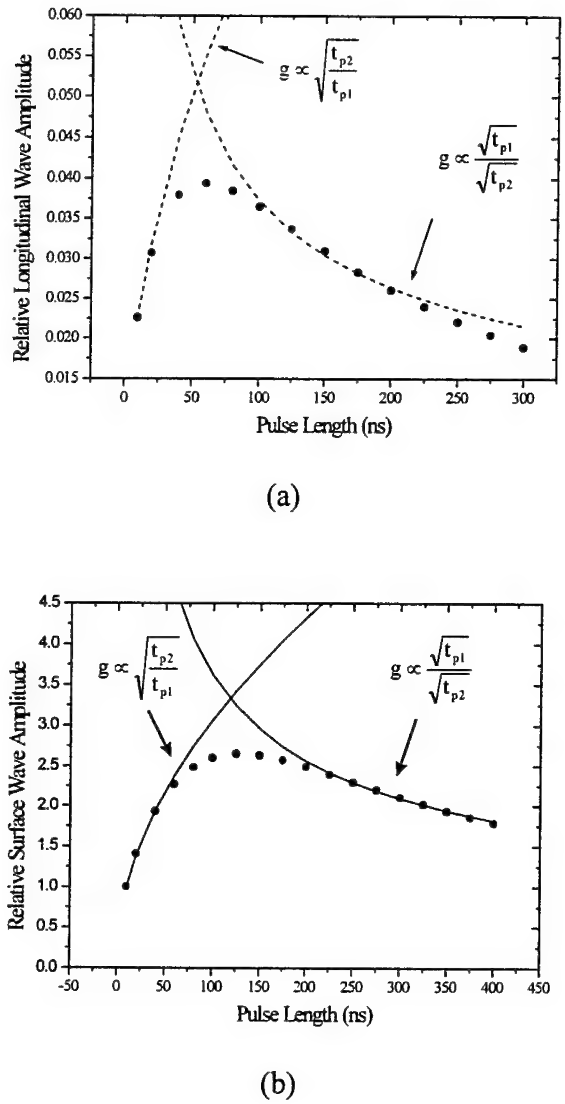

Figure 5: Ultrasonic wave amplitudes in aluminum as a function of generation pulse duration for fixed maximum surface temperature. As the pulse duration increases, the amount of energy delivered to the sample increases; however, at the longer pulse durations, less energy is coupled to ultrasonic modes. a. Longitudinal wave amplitude, b. Surface wave amplitude.

One final degree of control which can be exercised over the laser generating pulse is that of modulation, both temporal and spatial. The reason for considering either temporal or spatial modulation of the source is to generate signals which are more easily detected by the laser ultrasonic receiver. Modulation schemes enhance detectability either by reducing the bandwidth of the generated and transmitted signal or by increasing the ultrasonic amplitude by directing the ultrasonic energy to a specific detection point. In the first case, that of bandwidth reduction, detection sensitivity is enhanced by allowing the receiver system to be tuned for sensitivity only over the frequency range where ultrasonic signals have been generated. Consequently, the receiver is able to reject much of the broadband noise inherent to the detection and amplification processes. Signals which have restricted or narrowband frequency content are repetitive in time such as occurs for a toneburst. Such narrowband laser ultrasonic signals have

been generated by projecting the source laser onto the surface of a material in a repetitive spatial array so that at some receiving point, either on the same surface as the generation point or on an opposite surface but off-axis from the generation point, the arrival of sound generated from each element of the array is staggered so that instead of a single pulse, a sequence of pulses arrives at the receiving point [34, 35]. Alternatively, narrowband signals have been generated by temporal modulation, projecting a sequence of laser pulses at a single point on a surface using a variety of modulation and laser source techniques [36-41]. Regardless of the mechanism used, the bandwidth narrowing results in enhanced signal-to-noise ratio as can be seen from Figure 6.

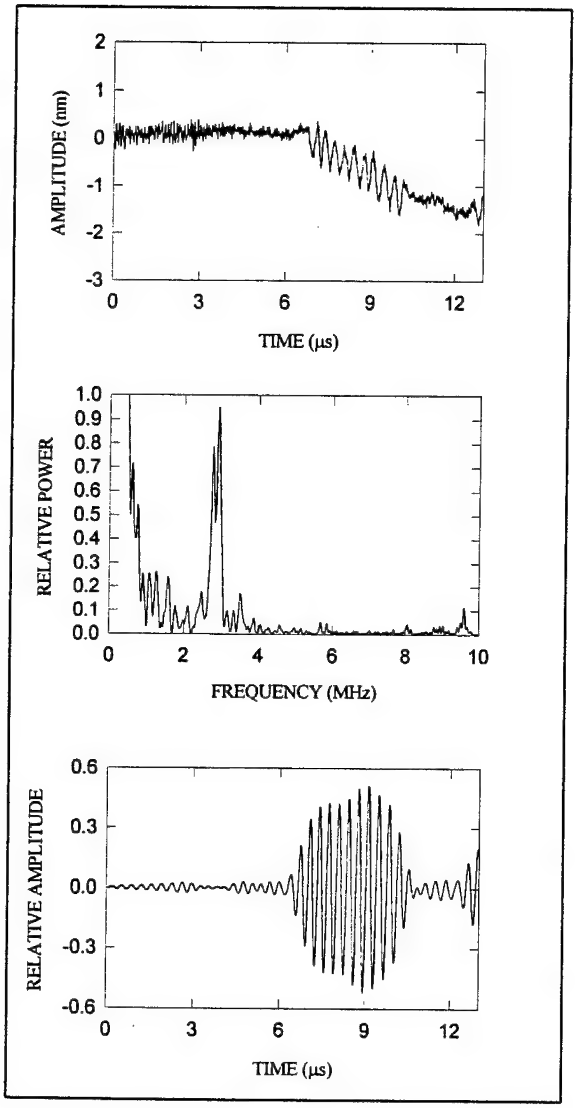

Figure 6: Laser generation of narrowband ultrasound applied to surface waves. a. Recorded ultrasonic displacements b. Power spectral density of recorded displacements c. Digitally filtered waveform displaying improved signal-to-noise.

By combining spatial and temporal modulation, it has been possible to produce single-pulse, broadband signals with large amplitude while still staying below the ablation damage threshold for the material. As can be seen from Figure 7, a time sequence of laser pulses arriving at the surface of the material in a spatial array pattern can be arranged such that the sound generated at each array element location arrives at the detector location at the same time, thus producing an enhanced signal [42]. The effectiveness of this technique, at least for surface waves, can be observed from the data shown in Figure 8. Similar enhancements are also achievable using modulated interference patterns on the surface of the material [43] or by sweeping the laser beam along the surface at the surface wave velocity [44]. In more recent variations on simple repetitive modulation methods are spatial [45] and temporal [46] modulation schemes to produce frequency chirped signals which permit simple matched filter processing following detection enhancing the detection signal-to-noise ratio. Chirp generation and signal enhancement is illustrated in Figure 9.

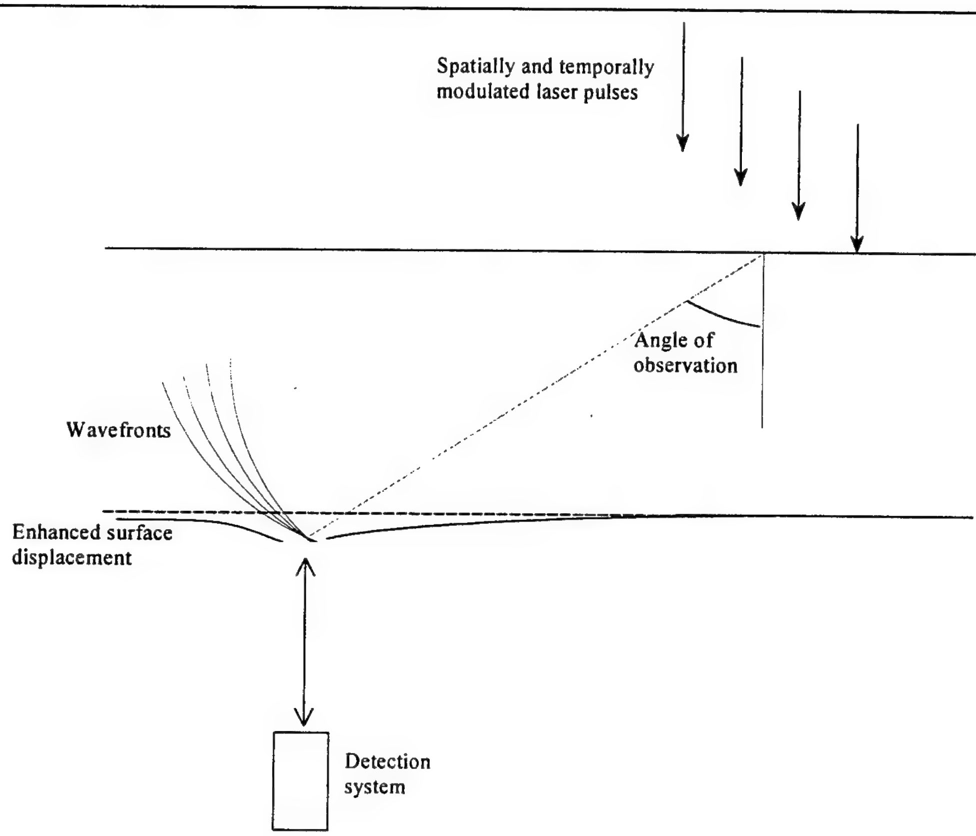

Figure 7: Experimental schematic showing phased generation of ultrasound for increased ultrasonic amplitude in a given direction.

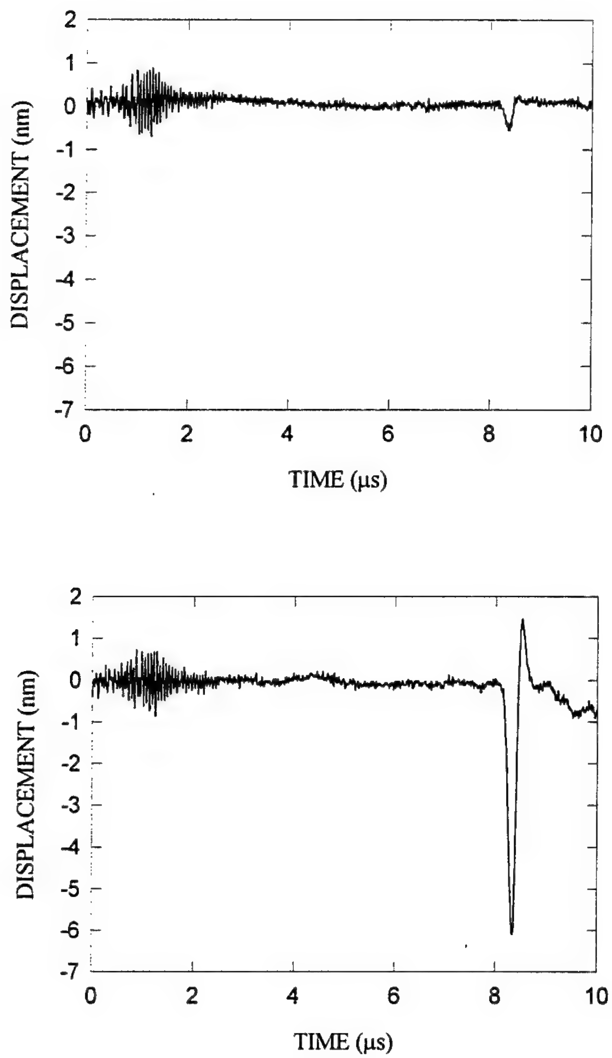

Figure 8: Experimental results for phased generation of surface waves. a. Surface wave from single laser array element. b. Enhanced surface wave amplitude resulting from surface irradiation by a phased laser source array.

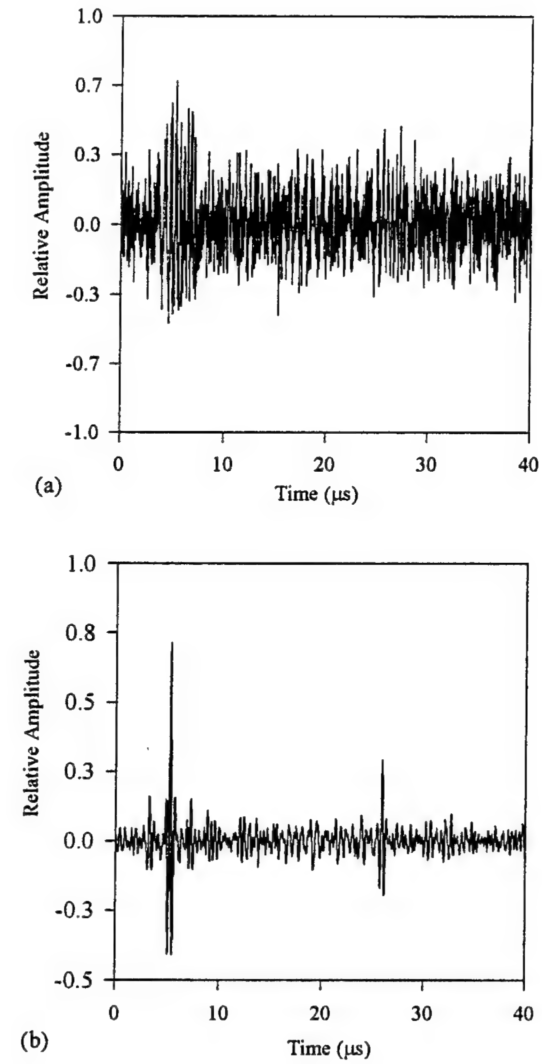

Figure 9: Experimental results for spatially chirped surface wave generation using a patterned laser source. a. Received signal at detector before processing. b. Signal-to-noise enhancement provided by signal analysis using chirped signal.

In constructing spatio-temporal arrays for improving laser ultrasonic signal signal-to-noise, various workers have used fiber-optic delivery systems [36, 37]. Fiber-optic delivery provides flexibility to the generation process since the source can be introduced to material surfaces not accessible using bulk optical components. Also, for a range of practical applications, laser pulse confinement within a fiber could decrease concerns regarding inadvertent exposure to the high power pulses used for generation. The use of fiber-optics for guiding the generating pulse has been pursued by a number of different research groups with the earliest reports appearing over a decade ago [47]. Unlike the telecommunications industry that was revolutionized by the introduction of fiber-based systems, fiber delivery of high power laser pulses for ultrasound generation has not progressed significantly since the early reports and the impact on the development of laser ultrasound systems has been minimal. Unfortunately, when subjected to the peak powers of generating laser pulses, optical fibers fail through a variety of damage mechanisms [48]. Typically, to decrease the power densities encountered, pulse delivery is accomplished using a mulitmode fiber which has a significant core diameter. Obviously, the larger the core diameter, the lower the fluence for a given laser pulse. Increased diameter also leads to decreased fiber flexibility and many of the advantages of fiber delivery are lost. Typically, 0.6 - 1.0 mm fiber core diameters provide a good compromise between optical and mechanical behaviors for Nd:YAG wavelengths [49, 50]. However, the maximum energy that can be delivered using these fibers is 25 - 30 mJ for a 10 ns pulse, marginal for ultrasound applications. Damage generally occurs by dielectric breakdown or by thermally induced material failure resulting in fracture of the fiber. In either case, large optical field amplitudes initiate damage. Generally, damage occurs at the input fiber face where scratches or other imperfections concentrate the optical field, inside the fiber where transverse field variations in the input beam are focused or along the fiber length where internal defects are exposed to the laser pulse. The last damage mechanism rarely occurs in the high quality fibers that are produced for optical applications. The first and second are more common and can be minimized by a proper choice for the generating laser and for the fiber preparation technique. Most of these damage mechanisms can be avoided by decreasing the peak power densities which can be accomplished directly by using longer pulses. For example, pulse durations of 100 μs have been used in constructing a laser array [51], but the resulting signals would be too small to be used for most laser ultrasound applications. Also, since many laser ultrasonics systems use either far infrared or ultraviolet lasers for generation, optical fiber delivery is not an option since fibers for these wavelengths are not available currently. Regardless, there do exist applications of laser ultrasound that could benefit from fiber optical delivery.

Once an ultrasonic disturbance is launched into a material, the laser ultrasonics system designer has very little control over the propagation of the sound through or across the material. After all, once the sound is generated, there is nothing special about the fact that it has been produced by the transduction of light

energy at the surface of the material. The sound simply propagates through the bulk material according to the laws of physics governing sound propagation regardless whether it was generated piezoelectrically or optically. However, the designer may wish to take advantage of the fact that the laser source produces multiple ultrasonic modes, including angled shear waves and angled longitudinal waves, from a single point, surface source. Beyond that, however, laser generated ultrasound will be attenuated, scattered, reflected, and mode converted in the material in the same way as ultrasound generated by more conventional means.

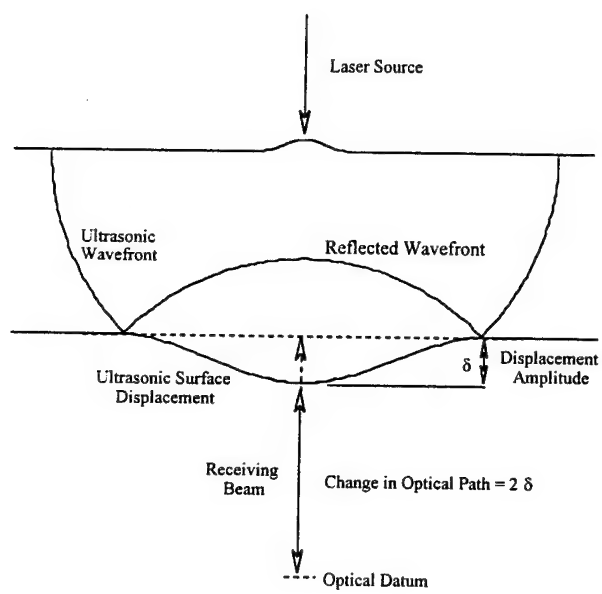

Figure 10: Schematic of surface deformation measured using optical interferometry. The ultrasonic wave produces surface displacements that are encoded in the phase of the receiving laser beam.

The process of detecting and measuring ultrasonic signals using a light beam, however, is distinct from piezoelectric detection. The detection problem is illustrated in Figure 10 where a surface displacement of an amount δ results on the surface from the arrival of an elastic wave. Experience and literature reports indicate that the displacement amplitude ranges from subnanometer values to several tens of nanometers. Most laser-based receivers evaluate the light reflected from the displaced surface for the corresponding changes in optical phase or frequency imposed by the surface motion. An optical phase shift results from the fact that the optical path distance from the receiving optics to the surface of the test piece is shortened by the amount 2δ during the arrival of the ultrasound.

Instruments detecting such phase shifts are often used to determine the actual surface displacement as a function of time with very high fidelity. Other instrument designs detect the slight change in optical frequency or wavelength imposed by the Doppler-shift when the detection point is being moved by the ultrasonic arrival. Both detection schemes rely on the principles of optical interferometry. The physics associated with the optical detection mechanism of several configurations have been summarized in prior review papers [52, 53, 54]. As for the choice of generating laser pulse characteristics, the appropriate choice of an optical receiver is highly application specific.

The need for application specific receiver designs stems from the fact that for most applications the detection sensitivity of an optical receiver system compares poorly with conventional piezoelectric detection. However, certain design parameters may be optimized so that for most applications a laser detection system can perform adequately and provide the user with noncontact and remote measurement capabilities. The design issues to be considered which can optimize the performance of a laser receiver depend on the amount and nature of the light that is collected after being reflected/scattered from the surface of a test object. For all optical detection systems, the performance is increased as the amount of collected light which can ultimately be focused on a photodetector is increased. For systems where the amount of collected light is sufficient such that the noise produced in the detection process exceeds that of the amplifying and processing electronics (shot-noise or quantum-noise limited systems) the detection sensitivity improves as the square root of the optical power collected from the reflecting surface [55]. For a material where detection can take place from a mirror-like or polished region of the surface, very sensitive optical detection of ultrasonic signals can be achieved with only a few milliwatts of laser power reflected from the surface. In the more general case, however, where surface color and roughness may absorb and/or scatter the laser light, the issue of optical collection efficiency can become a key factor in determining the ability of an optical system to be useful for a particular application.

Consider, first, remedies to increase the amount of light that can be collected from a diffusely scattering or strongly absorbing surface. Several solutions have been demonstrated. One solution has been to focus the interrogating beam to a small spot where a rough surface might be observed to be locally flat. In order to get strong retroreflection back into an interferometric detection system, alignment between the interferometer optics and the surface are required. However, this alignment requirement may be satisfied easily under a range of conditions. Indeed, sensitive interferometric measurements have been made using automated means for finding a bright speckle return from a rough surface [56]. Under measurement conditions where adjustments between the interferometer and the surface are impractical, laser ultrasonic measurements can still be made. The low average brightness resulting from scatter may necessitate many waveform averaging cycles to build-up a usable signal from repetitive excitation of the test piece. For

circumstances where low data update rates can be tolerated, poor light collection efficiency can be compensated with signal averaging. An additional degree of freedom afforded to the systems designer, when low data rates are tolerable, is the freedom to use unstabilized interferometry relying on ambient or imposed vibrations to move the system through its most sensitive operating condition [57]. Other means for overcoming the diffuse scattering from optically rough surfaces employ large collection optics often in excess of 30 centimeters in diameter. With large entrance pupils into an optical system, a greater solid angle is subtended so that more light is collected. However, the use of a large diameter collection optics introduces the complication that each ray of scattered light collected may have a random but static phase relationship with the other rays of light entering the same optics. Owing to interferometric considerations, when that light is ultimately focused to an image of the illuminating spot, it will not produce a uniformly bright or dark field. Instead, the field will be modulated by a static interference pattern referred to as speckle. If this speckle pattern is interfered with a uniform plane-wave reference beam, as is the case in conventional two-beam interferometry, displacement of the object surface will result in a twinkling of the speckle within the combined field rather than in a uniform, full-field variation of light intensity resulting from the surface displacement. Consequently, a different sort of interferometer is often employed when displacement or velocity data are to be obtained from a speckled light beam. One such interferometer design which has been applied very successfully for laser ultrasonic detection from diffusely reflecting surfaces is the Fabry-Perot interferometer [58, 59, 60]. The Fabry-Perot interferometer is able to interfere a speckle field arriving into the interferometer cavity with a second field arriving several nanoseconds later. If there has been surface motion within that time period, the Fabry-Perot interferometer produces an output related to the transient motion. In fact, the insensitivity of the Fabry-Perot Interferometer to very low frequency or static displacements is an added advantage of this system for use outside of a laboratory setting. More recently, there have been important advances in the use of photorefractive materials to permit interferometric detection of uniform phase or velocity measurements in speckled beams [61, 62]. Also, relatively new on the scene is a detection method based on photo-induced EMF (electro-motive force) measured within a photorefractive crystal in response to shifts in speckle interference patterns [63, 64].

5.0 Review of Reported Applications

Having explored the several options currently available for both laser generation and laser detection of ultrasound, it is clear that progress continues to be made at a rapid rate toward improving system detection sensitivity and reducing costs. Even while such advances are being made, however, numerous applications already have been reported. One of the earliest applications of laser ultrasonics used outside of the laboratory was performed at the Harry Diamond Laboratory of the United States Army where inspections for flaws in missile nose cones were performed [65]. In this application, a ruby laser was used and employed in a

strongly ablative regime. Interferometric detection of the output was received and variations in structural thickness and the existence of internal defects could be inferred. Another early example of the use of laser ultrasonics occurred at Lawrence Livermore National Laboratory where materials moduli at elevated temperatures were evaluated using a pulsed laser source with an unstabilized interferometric detector [66]. Again, ultrasonic generation was by material ablation and the resulting ultrasonic displacements were quite large. In subsequent years, more sophisticated applications of laser ultrasonic methods have been demonstrated. Several examples are cited below.

5.1 *Ceramics*

The utility of laser ultrasonic methods for measuring sintering density changes in ceramic materials was demonstrated in the late 1980's by investigators at the Idaho National Engineering Laboratory [67].

5.2 *Organic Matrix Composite Materials*

Owing to the need for military and aerospace composite structures to be inspected on a routine basis, there has been high priority placed on the development of large area rapid scanning laser-based ultrasonic systems [68-71]. Laser-based methods are especially attractive for this type of inspection since laser generation and detection methods can be performed on scattering surfaces without the need for perpendicular alignment to those surfaces. As was described previously, the eliminated need for perpendicular alignment results from the fact that ultrasound generated by the laser always propagates relative to the perpendicular of the surface of the material. Also, for a diffusely scattering surface, sensitive reception can also be achieved at off-normal angles. Owing to the strong emphasis for development in this particular inspection application, at least two systems have been installed for routine inspection and measurement use [72, 73]. These systems employ CO_2 laser sources with pulse durations of 80 to 100 nanoseconds for generation and use specially designed pulsed Nd:YAG lasers for detection which are operated in a long pulse mode (nearly 100 microseconds duration) providing very bright illumination for brief periods to ensure sensitive detection of the ultrasonic signals.

5.3 *Pipe wall Inspection*

Based upon long pulse Nd:YAG illumination for Fabry-Perot detection of ultrasound, wall thickness measurements have been demonstrated for seamless steel pipe production during the hot-forming process [74]. In this case, an eximer laser operating at ultraviolet wavelengths was used as an ablative source.

5.4 *Mold Filling*

Another process control demonstration using laser ultrasonics was the infiltration monitoring during resin transfer molding in simple geometries. Large area scanning of the mold was performed to ensure complete filling and lack of voids [75, 76]. In this case, the scanning laser ultrasonic system was used to pass sound through the mold and to generate an ultrasonic image during the resin transfer process. Empty regions and entrapped voids cause extreme attenuation of the ultrasonic signal, thus, providing image contrast.

5.5 *Weld Inspection*

Applications for determining the quality of a weld as part of a manufacturing and assembly process have been demonstrated by at least one investigator [77]. In one case, the inspection process was performed in near real-time by making laser ultrasonic measurements immediately behind a welding electrode. In the other, a special test fixture was used to inspect spot welds in small transmission components as an additional on-line inspection test.

5.6 *Polymer Film*

Inspection for thickness and uniformity in blown polymer films has been demonstrated using lasers to generate Lamb waves which, in turn, propagate a short distance across the film membrane before being detected. Lamb wave velocity is then correlated to film thickness [78].

5.7 *Packaging and Container Inspection*

The level of fluid contents within a rigid container can be determined from ultrasonic measurements. By employing laser ultrasonics, the same measurements can be made in a remote and noncontacting method [79, 80].

5.8 *Properties of Thin Films and Coatings*

Thickness and elastic constant measurement of thin metallic and ceramic films and coatings have been demonstrated as off-line techniques [81, 82] and as on-line process control sensors [83, 84]. In the latter case, the thickness of coatings deposited by physical vapor deposition (PVD) methods was monitored in real-time through an optical access window in the PVD reactor cell.

5.9 *Temperature Measurements*

For many materials, the velocity of ultrasonic waves can be correlated to the temperature of those materials so long as competing effects do not dominate. Ultrasonic methods for bulk temperature measurement are particularly attractive for materials at elevated, processing and forming temperatures. Some of the earliest work using laser ultrasonics as a sensor was performed for temperature measurement of metal alloys at high temperatures [66]. At processing temperatures in excess of 1000° C, contact methods for temperature measurement are virtually unavailable. Infrared pyrometry has been used with some success, but provides only an indication of surface temperature which for many alloys can be dramatically different from the average bulk temperature. With ultrasonics, it is possible to propagate sound energy through the bulk of the material so that its velocity provides some indication of an integrated temperature distribution. Once again, laser-based methods have the potential to make such measurements in a remote and noncontacting manner [85-88].

5.10 *Surface Crack Characterization*

The broad frequency content of elastic waves launched by pulsed laser excitation has been demonstrated to be useful in helping to characterize not only the location but the depth of surface breaking cracks in certain materials [89]. According to the frequency content, a broadband Rayleigh wave propagating along the surface of a material will be reflected or transmitted across a crack site. High frequency components with shallow depth penetration beneath the surface are

reflected more strongly than more deeply penetrating lower frequency components. By analyzing the spectral content of reflected and transmitted surface wave components, the depth of a surface-breaking crack can be estimated.

5.11 *Ultrafast Laser Ultrasonics*

Characterization of extremely thin films, down to tens of nanometers in thickness, has been demonstrated by several groups of investigators [90-95]. Common to all of these methods is the use of source lasers providing pulse durations ranging from sub-picoseconds to a few picoseconds. The use of short pulses ensures that discrete ultrasonic arrivals in thin films may be resolved in time and may be used to identify the ultrasonic transit time through the film thickness.

5.12 *Hybrid Methods*

Although each of the several applications mentioned above have been demonstrated successfully, there exist other applications for noncontact ultrasonic measurements involving lasers but for which the cost, inconvenience, or safety of an entirely laser-based system is not desirable. For some of these applications, hybrid methods have been demonstrated where lasers are used to generate the ultrasound but transducers using non-optical methods are used for detection. Electro-magnetic acoustic transducers (EMAT's) have been used for laser ultrasound reception owing to the demonstrated sensitivity of these transducers to shear wave motion in conductive materials [96, 97, 98]. Another hybrid technique which has been proposed and demonstrated uses laser generation and air-coupled piezoelectric transducers for detection [99]. The air-coupled reception technique exploits the presence of air as an ultrasonic coupling agent between the material and the transducer.

6.0 Comparative Capabilities

It is difficult to draw direct and valid comparisons between conventional ultrasonic methods and laser ultrasonic methods at a general level. More valid are comparisons for specific applications. For example, comparisons have been made of performance parameters such as scanning rate and resolution for applications involving large area inspection of composite materials for the aerospace industry [100]. However, there are many applications that can be addressed using laser ultrasonic methods but do not lend themselves to conventional contact ultrasonic techniques. The most obvious examples of these types of applications include those requiring noncontact and remote measurement. For applications to which either laser or conventional piezoelectric methods may be applied, it is the general case that laser ultrasonics is unable, at the current state-of-the-art, to provide the same level of sensitivity and data acquisition rate as its piezoelectric counterpart for a given capital cost. Often, a far greater investment in laser ultrasonic technology, sometimes as much as a thousand fold, is required to meet the performance characteristics of a piezoelectric-based ultrasonic measurement system. The nature of the performance limitations which lead to greater cost for a laser ultrasonic system are discussed in more detail in the following section.

7.0 Limitations

The performance limitations of laser ultrasonic systems have been alluded to already. Principally, these limitations may be overcome at the expense of safety and/or cost. The safety issue surrounding the use of laser methods for ultrasonic measurements is, primarily, the potential for eye damage owing to the extremely bright sources used for ultrasound generation. In a controlled-access setting, operators of laser ultrasonic systems wear safety goggles and can function freely in the test environment. For factory floor or field use greater precautions may be required to contain stray light which may be scattered by the inspection surface. Although consideration for eye safety is essential, safety issues are seldom the limiting factor to the broader application of laser ultrasonics.

Beyond safety concerns, it is most often the cost of laser ultrasonic methods which is cited as the underlying limitation restricting broader use of this technology. Certain costs associated with the use of laser ultrasonics might be categorized as being application specific. These costs include the expense for re-engineering a laser ultrasonic system for virtually each new material or application being considered. More restrictive, however, are the hardware costs associated with providing a level of detection sensitivity and data through-put rate comparable to conventional piezoelectric ultrasonic systems. Consider a laser ultrasonic system for large-area scanning inspection such as the system currently in operation at McClellan Air Force Base in Sacramento, California [72]. This system was designed to permit C-scan imaging of large areas of black graphite/epoxy composite materials used in the aerospace industry. As has been discussed already, a repetitively pulsed CO_2 laser was selected as the preferred nondamaging thermoelastic source laser. Recall, however, that to achieve usable detection sensitivities so that subnanometer surface displacements can be resolved, it is necessary to ensure that adequate light be collected from the surface during the detection process. In order to achieve the desired detection sensitivity, the designers of this particular system elected to incorporate a second pulsed laser not to generate stronger signals but as the probing light beam in the receiver system.

This receiving laser must necessarily have a much longer pulse duration than the source laser in order that its beam be interacting with the material surface and transducing displacements during the arrival of the ultrasonic signal. The pulse parameters for this receiving laser are such that the pulse duration is on the order of 100 microseconds with about a 10 microsecond window during which peak power, on the order of kilowatts, is directed toward the surface and collected by the receiver system. Although spread over a longer pulse duration, comparable amounts of light energy are delivered to the test surface during detection and generation. In addition to providing a longer pulse to accommodate measurement uncertainty, this pulsed receiving laser must also have extremely small phase and amplitude noise. Fluctuations in either parameter sometimes cannot be distinguished by the optical

system from displacements associated with the arrival of ultrasonic signals. As one might imagine, a low-noise, long-pulsed laser satisfying the requirements just described is not a readily available commercial item provided by most laser manufacturing concerns. Instead, lasers of this type must be custom manufactured at an increased cost over commonly available commercial units. Of the several systems currently operating using these long-pulsed detection lasers, the data acquisition rate still is on the order of 10 times slower than what is easily achievable with conventional piezoelectric systems. Increases in the data acquisition rate may be obtained using current laser technology; however, higher system costs well beyond those known currently would result.

8.0 Summary

Approximately 10 -20 publications concerned directly with laser ultrasonics appear each year as conference proceedings or as journal articles. Owing to the great flexibility of laser ultrasonic measurements, the contents of these articles are quite varied covering topics ranging from signal processing methods for improving signal-to-noise to new demonstrations of laser ultrasonic probing of biological tissues. Such diversity of effort and success with laser ultrasonics (as a single technology) provides the impression that a given implementation of the technology will address a range of ultrasonic sensing requirements. This impression is unfortunate. Generally, the central issues critical to the successful application of laser ultrasonics are well understood and have been discussed in this assessment; however, the particular decision path which must be followed to ensure success in a specific application is not known *a priori* and is often defined (incompletely) through experimentation. The design of a laser ultrasonic system for a specific sensing task could be accomplished through detailed engineering analysis; however, owing to the specificity of the result, the return-on-investment is rarely favorable.

Fortunately, the various technology demonstrations/applications listed in this assessment give valuable parametric information regarding laser ultrasonics use and implementation for specific sensing tasks and show that systems incorporating commercial components including, most importantly, lasers can yield important and useful results. In the near future, the costs of laser ultrasonic technology will be driven by the costs of source and detection lasers ; however, the converse is not the case. The cost of source lasers suitable for modest laser ultrasonic applications have decreased dramatically with improved functionality owing to the increased use of lasers in the medical, materials processing and communications fields. The improved performance-to-cost ratio for source lasers has raised the potential for commercial laser ultrasonic products which address a range of single-point, remote ultrasonic measurement requirements. Similar laser cost improvements for large-scale, scanning systems do not seem realizable in the near-term owing to the unique laser requirements, mentioned previously, for these systems.

Even though the ultrasonic inspection capabilities of these large systems are impressive, the most significant advances to occur in the technology center around the exploitation of the unique ultrasonic characteristics of the laser source and in improvements to the optical detection of ultrasound. Most laser ultrasonic tests use the laser source in much the same way that a contacting transducer is used to make ultrasonic measurements. Often such practice is sufficient to provide the desired information; however, it fails to use the laser source to its fullest extent. For example, the directivity of ultrasound from a thermoelastic point source in a strong absorber is well known, but there are few examples in the literature which attempt to use this directivity advantageously in designing a measurement system [79]. Current efforts to improve the robustness and portability of optical, ultrasonic transducers could aid in the development of portable laser-based ultrasonic systems. Such systems, if comparable to current laboratory systems in sensitivity, would broaden the application of laser ultrasonics to sensing environments which currently cannot be imitated easily in the laboratory. Owing to the difficulty in predicting the success of laser ultrasonics in a given task without actually performing tests, portable systems could prove valuable in the development and application of the technology.

9.0 Future Trends and Opportunities

Obviously, given the demonstrated successes of laser ultrasonic systems in laboratory measurements and the relatively limited number of corresponding results in industrial settings, there are barriers to implementation that prevent laser ultrasonic methods from being used even though the benefits from using the technology could be substantial. From a fundamental point-of-view, these barriers are primarily technological in nature; however, various human factors must be considered in connection with the barriers. In this section these barriers are identified so that the future funding for laser ultrasonics activities can be directed with maximal effect.

There are various required advances/developments which must occur if the anticipated capabilities of laser ultrasonic technologies are to be realized in a wider range of applications. These advances may be placed in five categories which are given in prioritized order as follows: 1. photonics technology 2. theory 3. data processing 4. human issues and 5. safety. The ordering follows from an understanding of the state of the technology. For example, safety is of central importance for any technological undertaking; however, if advances in photonics technology do not take place, then laser ultrasonics may not become a viable industrial sensor technology and will not require significant developments for system safety. Regardless, the required developments will be given briefly for each of these categories as follows:

9.1 *Photonics Technology*

To a significant extent, advances in laser ultrasonic sensor development have been predicated on advances in the photonics industry especially in the areas of

laser development and fiber optics technology. Practitioners of laser ultrasonics understand the photonics technology requirements; however, few if any have the resources to develop the necessary technology for ultrasonic applications. By far, the most important advances in photonics that are required are the development of high repetition rate lasers for use as ultrasonic transmitters. It would be desirable if these lasers were to have tunable pulse characteristics (wavelength, pulse duration, spatial profile) so that the source could be optimized for various materials. For the laser used in the reception system, superior signal-to-noise characteristics are needed. This means the development of high power, quasi-continuous lasers that have superior amplitude and phase stability. Cost effectiveness of these lasers is necessary; it is this cost that makes laser ultrasonics systems unattractive to many potential users.

For applications where optical delivery using fiber optics is desired, fiber development for far infrared and ultraviolet wavelengths is necessary. For many applications, it is desirable to have these source wavelengths for optimal material interaction; unfortunately, it is at these wavelengths that fiber technology has failed to make significant progress. Also, fiber optic delivery of the source laser pulse has concentrated on coupling light out the end of fibers. Conceivably, light could be evanescently coupled out the side of a fiber at multiple points along its length [101]. If successfully developed, this approach has some advantages compared with more conventional fiber-based systems since, if the fiber is embedded in the material to be interrogated, sound can be generated at various critical points in the structure simultaneously and potential exposure to the generating pules can be minimized. Distributed fiber-based laser ultrasound delivery systems could be coupled quite nicely with existing distributed fiber-based sensors such that source-receiver pairs could be used to locally interrogate a material structure at predetermined points where material failure is anticipated.

Even with the use of fiber-based delivery, optimizing the material interaction for the elimination of material damage often dominates the selection process for the laser source. For repeatable ultrasonic results, the source region in the material must remain unchanged by the laser pulse interaction. In metal alloys, the selection process ultimately dictates the use of x-ray sources for ultrasound generation owing to penetration depth considerations. Unfortunately, little research has been conducted in the area of x-ray source development.

9.2 *Theory and Modeling*

The concern for surface damage extends to consideration of the ablation processes in materials. Current models for ablation do not allow for predictive uses such that the optimal source characteristics may be defined *a priori*. Non-experimentally-based, source optimization for ultrasound generation without ablation could simplify and improve system specification.

Currently, there is little analytical development guiding the important materials properties measurements that could be performed using laser ultrasonics (adhesion strength at boundaries in layered structures, hardness gradients at surfaces, residual stress measurement). This is especially true for laser ultrasonics

where the broadbanded laser source generates multiple ultrasonic modes simultaneously. The presence of all of these modes at a range of frequencies allows for analysis beyond that developed for conventional ultrasonics.

9.3 *Data Processing*

The desired developments in data processing include advances in the hardware of data acquisition and in data analysis algorithms to increase data processing rates (parallel architectures, customized processing electronics). Again, ultrasonic signal-to-noise impacts data acquisition requirements since improvements to transducer signal-to-noise reduce the digitization depth required for signal capture and processing and produce increased data transfer and analysis rates.

9.4 *Human Issues/Factors*

Currently, it is not clear that a critical mass of researchers/workers in laser ultrasonics exists such that successful transfer of the technology can occur from the laboratory to the industrial environment. It is noted that even if laser-based ultrasonics systems are adopted for use by a number of industrial users then there does not exist a program in which technicians familiar with the technology may be trained. Essentially, the number of workers familiar with the technology, from the research level to the shop floor level, may be too limited to successfully implement the technology in a significant number of critical applications.

9.5 Safety

As is the case for many sensor technologies, there are safety concerns which must be addressed for users of laser ultrasonics. The most significant safety concern is the potential for permanent eye damage which can occur from exposure of the eye to the source laser pulse. Currently, pulsed laser technology exists that has been shown to be "eye-safe." Laser radiation at 1.54 mm is absorbed in sections of the eye (the vitreous humor) that do not suffer permanent damage as a result of exposure to the laser pulse. Pulsed laser operation at shorter wavelengths can cause retinal damage; at longer wavelengths, retinal or corneal damage. Whereas pulsed lasers at the eye-safe wavelength have not been used for laser ultrasonics applications, it would be useful to evaluate the utility and safety of using eye-safe lasers. Additionally, no OSHA approved laser ultrasonic systems exist. For significant industrial use of the technology, such approval is believed to be necessary.

Over the past 15 years, there have been few research groups in North America that have been able to show significant and sustained industrial demonstrations of laser ultrasonics technology. Perhaps, the only true development efforts in laser ultrasonics (where significant alterations to laser systems have been pursued to enhance the performance of laser ultrasonics systems) have occurred within these groups. It is noted that these are the only groups that have experienced any measure of continued support at significant levels during this time frame.

Many other research efforts in industry, government and university settings have concentrated on the analytical and experimental aspects of laser ultrasonics; however, most of these efforts have relied on commercially-available lasers, optical hardware, data acquisition systems and computer systems. Generally, these other efforts have been relatively low-cost, of short duration and have resulted in small-scale technology demonstrations in the laboratory. Regardless of the ingenuity of the researchers involved, it is clear that more numerous and more substantial demonstrations of the technology have not occurred owing to the low-level of support provided for the technology by government and industry.

As has been demonstrated, laser ultrasonics can be used successfully in the industrial environment; however, numerous studies have shown that the design of the laser ultrasonics system must be tailored to the material for which measurements are being made. Generic laser ultrasonics systems are of limited utility and cannot be expected to yield optimal results in a given application. Too often, sensing applications using laser ultrasonics have yielded poor results; however, just as often, the technology has not been designed/implemented in a manner which would yield acceptable results. Clearly, it is only through realistic appraisal of the capabilities of laser ultrasonics and of the required sensor information that the technology can fulfill its promise in industrial inspection environments.

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Appendix

Transcription of a Panel Discussion on Laser Ultrasonics

June 17, 1997

Boulder, Colorado

PANEL DISCUSSION OF LASER ULTRASONICS

Eighth International Symposium on
Nondestructive Characterization of Materials
Boulder, CO
June 17, 1997

Foreword by Panel Moderator

The following is a transcription of the laser ultrasonics panel discussion held at the Eighth International Symposium on Nondestructive Characterization of Materials, Boulder, Colorado on June 17, 1997. The members of the panel were invited by James Wagner to share their thoughts on the state of laser ultrasonics technology to aid the direction of research resources in furthering the state of the technology. Unfortunately, owing to illness, James Wagner was unable to serve as moderator for the panel.

The panel members were selected from university, government and industrial laboratories. The participating panelists are given as follows:

Richard Dewhurst, Univ. of Manchester Institute of Science and Tech., Manchester, England
Thomas Drake, Lockheed Martin, Fort Worth, Texas
Curtis Fiedler, Wright-Patterson Air Force Base, Dayton, Ohio
Andrew McKie, Rockwell Science Center, Thousand Oaks, California
Jean-Pierre Monchalin, National Research Council of Canada, Boucherville, Canada
Gil Dunning, Hughes Research Laboratories, Malibu, California
Stuart Palmer, University of Warwick, Coventry, England.

A review of the references contained in this technology review indicates that various members of the panel have contributed significantly to the development and application of laser ultrasonics over many years.

The preliminary remarks given by Timothy McIntyre, U.S. Department of Energy (DoE), were not intended to be part of the actual panel discussion. However, the remarks made by Dr. McIntyre led to the convening of a workshop on laser ultrasonics technology in December, 1997 that was organized and hosted by Robert E. Green, Jr. at The Johns Hopkins University. The reader is referred to the proceedings of this workshop for further information on laser ultrasonics for industrial applications (*Industrial Applications of Laser Ultrasonics*, workshop report, sponsored by the U.S. Department of Energy, Office of Industrial Technologies, March 1998).

Transcription of Panel Discussion on Laser Ultrasonics

Tim McIntyre: improve research efficiency ... what that means is reduce energy consumption and reduce waste generation, and we perceive laser ultrasonics as a sensor technology which may be very useful in doing that. The industries we're talking about when we talk about these kinds of things are these seven, some of which you've heard about in the last day or two. The real reason I'm standing up here is that we have discussed this among some of the teams at DoE, and we feel like there is considerable opportunity to do some additional work and so we would offer to you folks who are the experts in this field to come to Washington and have a workshop, maybe in the late summer or early fall, to discuss what kinds of things we might do if we had a continued research program relevant to these industries. Keep that in mind always when dealing with this office, at least. And so, anybody who might be interested in doing that, I would really-appreciate your giving me your business card or scribbling on a piece of paper or whatever, and then we would like to have a one- or two-day workshop and discuss some of the things that you're doing and what are the issues with regard to getting these systems into the plants. Bring some examples of some systems that are kind of being used in industrial applications. Some of the applications these guys have are much more nasty than what you've heard here today, and they really want to get these things as close to the process as possible. So, I think there is some work to be done there. And there may also be some work in the areas of just measuring some things that they currently can't measure. And so, anybody who might be interested in participating in that and maybe participating in some continued research, there may be some considerable money available here so give me a business card or scribble something down on a piece of paper... And I have business cards if you'd like mine and...

Audience Member: Don't say anymore. - -

Laughter in the room.

Tim McIntyre: Thank you.

Jim Spicer: Good afternoon. I'm Jim Spicer, and I'm one of the two panel moderators for our panel discussion on Laser Ultrasonics. The other one is Curtis Fiedler from our Air Force Wright Laboratories, and I think this forum presents a unique opportunity to discuss the state-of-the-art in laser ultrasonics and critical issues connected with the technology with some people who have a great range of experiences in the field. The way we're going to be organizing this panel discussion is there are six questions which Jim Wagner wrote down and gave to the panelists before coming here approximately 10 days ago. They've had a chance to look at those and try to form some thoughts on how to respond to some of these questions. As they formulate their response, we hope that other panel members will contribute

to a given answer and then we'll open up to the audience for discussion and try to get contributions from audience on various aspects of the question. The proceedings of the panel discussion are being tape recorded, and we have the microphone up here which is going to be recording the comments of the panelists, in particular, the audience, and we're going to transcribe those and prepare a report which essentially reflects the feelings of the people who work in laser ultrasonics on what the state of laser ultrasonics is.

Our panel of participants today are Richard Dewhurst from the University of Manchester, Institute of Science and Technology. If you would stand up, please, so everybody gets to know your face. Unfortunately, our panelists are low and they're going to be difficult to see, but they're going to be speaking into the microphone, I hope so. Richard Dewhurst. Our second panelist is Tommy Drake from Lockheed Martin-Fort Worth. Our third panelist is Andrew McKie from Rockwell Science Center; Jean-Pierre Monchalin from the National Research Council in Canada. We have Gil Dunning, substituting in for David Pepper today, from Hughes Research Laboratories-Malibu; and we have Stuart Palmer from the University of Warwick, Department of Physics; and, finally, we don't have a spot for Jim Wagner and I'm substituting for him today as best I can.

As the panelists answer the questions, I would ask that you give your name so that when it gets on the tape, we know who's giving the response. And also when someone from the audience wants to ask a question, I ask that you stand up and identify yourself, and if I have time, I'll try to run you down and get the microphone in front of you so everybody can hear you. O.K. So, with the preliminaries out of the way, and I don't want to take too much time away from the discussion, these are some of the broad areas that Jim Wagner wanted to be touched on in the discussion. I'll just leave these up here through the duration of the discussion to try to channel our thoughts as we're going along. We're going to have some overheads and a pen up here, so that if you feel compelled to write something down, please jump up and write it down so that we can clarify points. But what I think we'll do is we'll just get to the questioning. I have a longer form for the questions here that I'm going to read from.

The first question connected with emphasis on assessment of the technology, the technology being laser ultrasonics, is, in your view, if anything, what limits the broader use of laser ultrasonics? Is it cost? Convenience? Safety? Lack of user familiarity? Materials specificity? Expectations that laser ultrasonics should give... replacement for conventional UT? Also, often when people see the promise of laser ultrasonics, they want to get into it right away without considering all aspects of the technology. We'd like to try to identify what limits the broader use of laser ultrasonics. Would anybody on the panel care to address that question particularly. If nobody volunteers, I will volunteer something.

Stuart Palmer: Want a comment on limitations?

Spicer: Absolutely.

Palmer: Then I'll start up with some very simple ones and people, I'm sure, can build on them. First of all, if you take the generation system, you're going to meet objections and problems when you're using lasers for generating, particularly if you want to use those lasers in a way in the ideal environment for a remote nonconducting system. That's a hostile environment where you might have steam, you might have smoke, you might have all sorts of stuff in the atmosphere and therefore to get the laser to do test piece, you've probably got to use fiber optics and limitation of the fibers is the amount of energy you can get down the fiber optic, particularly if you want to use a **C02** laser, and you can't get any energy at all. There are notations on the generation side.

On the detection side, the limitations, I think, are even more severe. We've heard about them yesterday and we've heard about them today. But if you want an interferometric detection system, there are now a whole range of competing interferometers, all of which have advantages, all of which have significant disadvantages for a range of applications. We've heard about the Sagnac, we've heard about the photo-refractive, we've heard about the Fabry-Perot, we've heard about the Michelson, and there's a cost problem, there's a sensitivity problem, there's a delicate nature problem, a whole range of problems that still have to be addressed to bring those interferometers into the workplace to do new jobs. There are problems on both sides - detection and generation.

Jean-Pierre Monchalin: I'd like to say that technology has been brought already to the real world, meeting specifications in steel mills, a production system which has inspected composite material. So there has been a lot of progress. What would be the ultimate dream for laser ultrasonics would be to replace completely conventional ultrasonics. Do not be .... We are less sensitive by, I would say, two orders, three orders of magnitude for us push forward in our research, that would be to try to improve sensitivity. To improve sensitivity by another order of magnitude would open many applications; to improve by two orders, even more. What's even more difficult, we have to do that without increasing cost and probably with decreasing of the cost. One obstacle of laser ultrasonics relative to conventional ultrasonics is the cost. So for our application, we should pick an application where our technology and cost associated with our technology make sense; when conventional ultrasonics cannot be applied because of temperature, rough environment, location, complex shape, etc. So we should not try to push the technology where other competing technology, especially conventional ultrasonics, could do a proper job.
Think application ... to monitor ... contact probably is not to be done for research but ... application which of the limitations which will be minor will be laser safety. We

shall try to put laser system in the factory environment, open air. You have to deal with the sight issue and to have a safety plan and with laser ultrasonics, you have the lasers; one could be eyesafe, but it is very difficult to have two eyesafe, because generally you have generation wave length different from the detection one. So that's going to be a limitation. I think I've spoken enough and may come back.

Laughter.

Spicer: You've spoken in particular, that laser ultrasonics perhaps isn't the technology to replace other technologies in certain applications.

Monchalin: Yes.

Spicer: I understand that. I think Stuart Palmer, in his talk at the conference when he was talking about gauging liquid levels in beverage cans, pointed out some of the reasons that guided them to solutions that they took in addressing that particular problem and instead of using lasers to pick up, used EMAT's because that technology made sense, and I was wondering if somebody on the panel would care to essentially outline those unique applications where laser ultrasonics has been found to uniquely address a problem.

Tom Drake: This one is directed towards me.

Laughter in room. Banter.

Drake: Yes. That's exactly our situation. The large usage of complex contours in aircraft and structures made out of composites is just now s starting. If you look at high volume aircraft like the F-16, there's very little composite usage ;tail sections are relatively flat. They're easy to test with traditional units. Flat parts, no problem. Going to all composite aircraft which we'll have in the future eventually, the first locations we've already shown that we're ten times faster than the conventional approach. Conventional techniques could get faster but it's more difficult. One of the problems is if you watch the guys setting up the first time testing a part, it may take him days the first time he loads that part in the fixture and teaches the part contour. I look at that problem and say, "Go out and use an optical method to describe the surface an then go test it," but that would defeat laser ultrasonics, so don't tell anyone. Needless to say, I don't need to know the shape of the part before I test it. We didn't need this 5 or 10 years ago; we need it for the next 10 years.

Spicer: I'd like to return to Curtis' comment he made in his talk about using laser ultrasonics to inspect complicated shapes caused designers to make even more complicated shapes. Would anyone else on the panel like to comment about broad use of laser ultrasonics and what's been done?

Gil Dunning: Gill Dunning, Hughes Research Laboratories. There's a culmination of both scientific and non-scientific reasons on the acceptance of LBU (laser-based ultrasonics) used in industry. As we heard, there was talk about improving the sensitivity. However, there are unique markets now that you can address with the current sensitivity levels, and I think it's very important for us to identify these specific niche markets for laser-based ultrasound and have a success story that we can point to and say, "Here's a system that's been operating 24 hours a day, 7 days a week, months on end." But when we try to introduce laser-based ultrasound in industry, we run into an inertia in the form of "we've been doing it this way; it works;" and they have a lot of inertia against changing, even though we can get them more data in a shorter time frame. So, all of it is you have to establish laser-based ultrasound as the preferred technique and demonstrate hands down that this is the best way to do it.

Spicer: Is that going to also... I guess that also holds true for the implementation of laser ultrasonics in applications where other technologies are not really competitive.

Dunning: That's part of the uniqueness that's well suited for laser-based ultrasound.

Andrew McKie: In addition to Tommy's comments about the inspection of complexly
contoured composite components, it's really that the laser is adaptive to any complexly contoured material whether it be composite materials or metal materials. Another reason, another application area that the laser is really suited to is in-situ process monitoring. Gil showed an example today of some cure monitoring applications, and I think there's a real need to identify the niche markets, as has been said before. A good example of a success story is Harry Ringemacher's success in the monitoring the chemical vapor deposition process at 1200 °C in a reactor. That is really a great success story, and I think we obviously need more of these applications to make it into industry. We've seen a number of great success stories this past week, and it's really a problem of user familiarity, too. People in industry tend to be rather skeptical of laser-based ultrasound. They come into a lab and see a table stacked with mirrors and you tell them you have five different experiments going on, but they really have a hard time seeing past all this optical hardware. I think that it's really hard for them to grasp that this could really be implemented in many industrial environments.

Spicer: In terms of cost, we talked about stacks of equipment. The issue of cost,--is that something that would be easily addressed or does that limit the application of the technology?

McKie: I'll continued on. I think the big problem is, with a conventional ultrasonics system, you can go out, buy your transducer, buy your pulse-receiver, so you've got a very small setup fee. You can go off, you can test your material, , and if it works for you, then you can invest more money and solve your problem. With a laser, certainly, the entry fee is pretty steep just to even test the waters and get your feet wet and see if it's appropriate for your needs, <u>and</u> so, it causes a real problem in that aspect.

Richard Dewhurst: Just going on about it, if we take an ultrasonic technique, we can go out and buy a conventional system, we've got a little knob on the front of the box, and we can swing our dynamic range of our testing system over maybe 60 dB or 80 dB. When we go to a laser ultrasonic system and we look at the dynamic range of the particular system at the moment we've had figures... these last two days of perhaps 40 dB dynamic range. We have to work a little harder at a wider range of measurement sensitivity, a wider range of displacement, given that one particular system so that we can then take that system to a number of applications and we will offer a reasonable measurement tool.

Spicer: I think we'll get back to following up on that, so hold that thought. Are there any comments from the audience?

Marvin Klein: My name is Marvin Klein, Lasson Technologies. I think you have to be a little careful how you judge cost because I think you should, with any system but especially a laser system, you have to address the cost to the user, not just the cost in absolute dollars. If he gets a payback on his investment in 6 months and had to spend a $100,000 to do it, he'll be a happy guy, I would expect. So I don't feel people should get too hung up. I think it's always worth while to make costs as low as possible. Everybody is interested in that for obvious reasons, but I think you do have to be a little careful when it's industrial applications payback that really is going to determine the effectiveness of your product.

Bob Addison: The system cost depends on the ROI, and if the ROI is there, people are going to pay it, and for an AUSS system these days, I think they are going for $2-1/2 million a copy. And in our composite plant now, we have three of them. We've had as many as five because the cost was justified. Compared to that cost, I don't think the total laser ultrasonic system cost is that great. But it's this idea that you have to pay so much just to play the game at all.

Spicer: Any other comments or questions?

Dunning: Gil Dunning. One of the things that they've done in the semiconductor industry, which is kind of unique, it might be a good model, would be that they have foundries, if you give them a design for a circuit layout, they will generate the chips for you. And maybe if we had something similar in laser-based ultrasound, some

testing facility that people could send their parts to and see if laser-based ultrasound was even applicable, then this might be a way we get this out to the community out there, cost effectively.

Spicer: In terms of the issue that Richard Dewhurst brought up in terms of dynamic range, could the second question that was written down here for discussion was, "Identify the current research activities which are addressed towards resolving the limitations of dynamic range," and I was wondering if any of the panelists would care to comment on what they felt was either presented at this conference knew about otherwise that is currently being part of a research effort.

Curt Fiedler: Specifically from an Air Force point of view, interest in inspecting air craft, especially aging aircraft, and we do have research money available still, and the question is, yeah, if we were to allocate this money to try to get the highest payoff, where would that be? And while we are interested in specifically aircraft, it would also be nice to look at other applications, too.

Spicer. Anybody else like to comment?

Dewhurst: I think we heard from Jean-Pierre Monchalin one of the ways in which they're addressing that area of sensitivity. We're here now in 1997, with small powerful computers, so that not only does the possibility of performing signal averaging, but using better signal processing techniques in order to reduce the minimum displacement sensitivity that can be detected. And that's the route to go to enhance the dynamic range in our systems. It may well be that those electronic computer devices will help us in choosing systems which are going to be more cost effective.

Spicer: Anything you have in mind in particular?

Dewhurst: His talk gave a very good example on what type of signal processing which would assist bringing out those displacements. Before we had to either increase the power, as the square root of "P" to increase sensitivity, you've got the square root of the bandwidth, let's reduce the bandwidth, and I think now that there are some other enhancements which could be brought about with signal processing.

Spicer: Do you care to comment on that?

Monchalin: Yes. When trying to improve sensitivity that your limit is ???.... To have a receiver... is good because you improve the sensitivity range of frequency which could be useful, low frequency or high frequency- and be open to a new application. Because some applications you can look for require particularly low frequencies, other application which require much higher frequencies. From the

research point of view, pushing up the sensitivity or pushing down the detection limit should be ... research.

Spicer: And you quoted in comments earlier that a factor of 10 would be something that you sought after?

Monchalin: Yes.

Spicer: Is that achievable?

Monchalin: I don't know. I don't know. You have to realize that we are less sensitive than
the conventional ultrasonic technique... so that the application we cannot do because we cannot damage the part, we cannot use much power for generation, of course, we have high power generation but to see.... ???

I want to add something that has not been mentioned and Jim was involved. .... transducer. This is another limitation of our activity that we are using the material as our transducer. So we are somehow... conventional ultrasonics where they use an external device to produce the ultrasonic wave.

Spicer: So that with materials that are easily damaged, it is difficult to get a good signal?

Monchalin: Yes, so that with laser ultrasonics, it would be very difficult for us to even figure the sensitivity of detection to replace the conventional technique. That is why laser ultrasonics is going to be, probably for a long time, a niche technique, with specialized application; not a technique to be applied to all kinds of materials in all types of applications.

Spicer: Would anyone else like to comment?

McKie: I would like to follow up on what Jean-Pierre said about the basic material specificity, something we've known about for a long time. We've been exploiting inspection of composites because it was a very good material and lended itself very well as a transducer. I think we're still learning which materials are the best materials for the laser application. Curt had mentioned that they had done some work at McClellan AFB, and they found some materials that really don't work very well at all. So, you know, the materials specificity is something we have to take into account, and in the work we're doing ourselves, we have to apply paint to a metallic substrate. If you can tolerate that, then it's all well and good. These are things that have to be taken into account.

Drake: I might make a comment. What we're talking about now is a range from good to bad. That's really what we're getting at when we talk about composites. One thing you'd like to know is what is that range? Is it a factor of 100 between good materials and bad materials, because as Jean-Pierre pointed out, a factor of 100 may be difficult to get. We've found it's more like a factor of 10, between cured composites, different surface conditions, painted or unpainted, different types of peel plies. It's not two orders of magnitude (but) more like a factor of 10, which means for most of those materials, these are structural type components we use in aircraft. They fall in a relatively small band which we need to deal with. These are organic based composites, not metal matrix. The types of parts you're going to find on aircraft.

Spicer. Has anybody seen, among the issues concerning laser ultrasonics, the ability to understand what the signal represents? All too often in a lot of these talks, I see where you're looking for a longitudinal wave, straight through and straight back, to mimic conventional ultrasonics. Any thoughts with regard to research activity that should be directed toward making a more comprehensive understanding of the wave interactions that can occur in complexly shaped parts?

Drake: In our case, we want it to look just like conventional ultrasonics. We don't want any deviation. Because we want the guy on the factory floor to be extraordinarily comfortable, we're not planning to do additional certification of those types of things They're fairly satisfied. When they look at the signal as the system runs, it looks like ultrasonics and makes them feel really good. We actually like the fact that it's treated the same, in fact, that's what we usually tell them. If you have difficulty interpreting the signal, you would have the same difficulty with conventional ultrasonics. But in some cases, some composites are very complicated structures; they can have T-sections. In that case, pulse echo is just not a very appropriate test to begin with. So it doesn't mean we won't to apply it in that case, but it's still not the best test.

Spicer: Anyone want to comment on this?

Dunning: I think the main benefits of conferences like this is that you're listening to talks about people identifying the best metric for a particular testing or evaluation. And that's important when you start talking to the customer that you can apply the metric that identifies their problem. Also, another thing that we've run into is that you have to acquire the data in the appropriate time frame and you have to display it in a manner that they want. Oftentimes, they would like just a thumbs up or thumbs down. Sometimes they would like trending information so you need to be able to provide that for them. But in the end, they don't really care if you've got that you've got laser-based ultrasound in the black box. They have a process, and they want to control that process. Even though we're in a ...

(Tape ended and turned.)

Palmer:... in financial troubles and that industry, for a while, were reluctant to put any more money in. I had the good news that in the near future they've got some more funding to continue that work. From the European perspective, we're also, in the European steel industries, struggling to persuade them that the cost of laser-based ultrasound is worth investing in for this type of program. Yes, they realize that laser-based ultrasound is the only way to monitor very hot steel as it comes rolling out of the furnace. The cost of the system, particularly the interferometer detector, is at the moment prohibitive. If we could bring the cost down while maintaining a reasonable performance, then it would be a niche that could explode in interest worldwide.

Petros Kotidis: Petros Kotidis, Textron. There's also another point that I think someone alluded to, but in this industry, the laser ultrasonics industry, we're lacking a champion, a commercial champion, if you think about it, and the reason is that most of the work has been focused on either applications like the Air Force, General Dynamics, Rockwell, places where tremendous work was done and very successful, but it was for specific applications. I think this is actually a classic situation. Most industries have gone through this growing thing which is, in the imaging industry, the same thing happened; the pyrometers and the IR imaging, the same thing happened. It started very small and slowly it grew, but there was a champion. There was a commercial champion who went out there, put money into this, and took the risk of running the field test, writing the experiments, and all that. So, it is not so simple to just say that we will find an application in a niche market and someone will come to us. It has to be supported.

Spicer: I think that's a good point, and I think that brings us to our next bullet, "What should be the roles of government, industry, and university?" On our panel we have academics represented, industrial people represented, and government people represented. What are your thoughts on the roles of your various institutions in contributing to laser ultrasonics?

Monchalin: We think we should do what industry cannot do. Rather in this... university should be prominent.... in theory. Industry should look more at developing and making the technology practical. The government lab probably should go between trying to demonstrate the technology, invest in demonstrations which are very costly, difficult, very risky, so each center has more specific work toward this.

Spicer: So, who is the champion amongst these, then?

Monchalin: It could be a big company. I don't see the university. (Laughter) because there's a lot of practical technology, a lot of engineering. ... The university should contribute on knowledge and, to a lesser extent, on engineering.

Spicer: I agree with you. I also would put forth sometimes that's difficult in a university without the technology. Sometimes we don't have the equipment that's available to the people who've done the engineering to investigate various issues.

Monchalin: That would mean that the funding agency should allow the university to get proper equipment.

Laughter.

Dewhurst: Of course, what we know in reality is that there is a sort of incestuous marriage between university, government institutions, and industry that try to bring about a new set of systems, and laser ultrasonics is one of those fields of interest where all the centers have played their part. Yes, the universities should play a more fundamental level and address some of the scientific issues. I'd like to give an example and a challenge that's been bothering me for at least five years. That is that many of our optical detectors that we have in our interferometer systems, see on that detector, a DC component and an AC component. Andy McKie mentioned the fact the other day that saturation of our detectors is one of the reasons that limits our dynamic range. The saturations are caused by the DC component that doesn't have any of the ultrasonic information on it. How can we remove that DC component of the detector? If we can remove that part which saturates, life would be a lot simpler. And why can't it? Because electronically we have an analogy, we have voltage, an AC voltage on top of a DC voltage. We have a simple component called a capacitor. It is a passive device, and it separates the two. We need the same sort of passive device. Now that's the sort of thing that universities maybe should be addressing.

Klein: I think that's a good point. There is one detector for sure that doesn't have a DC component, that's the photo EMF. There's one thing that I wanted to point out, and that is an advantage, dynamic range. Most of the other photo-refractive devices do have a DC component, but there is a bright side, and that is the DC component tells you the amount of signal you are receiving. You can use that to normalize your signals, if that's important for you. So there is one benefit of having a DC component. Thank you.

Dewhurst: Until saturation sets in.

Wolfgang Sachse: Wolfgang Sachse, Cornell. I agree with everything that's been said, but I think that especially, Jean-Pierre, I think that evolutionary changes will

come from terrific institutes and laboratories, like where you are, and if you are going to look for a revolutionary change, and I think you started touching on that, of taking a quantum jump, a new idea, I think that has to come possibly from universities.

Monchalin: I agree with that. Universities should look at the fundamental physics, long-term,
high risk scientific devices.

Dewhurst: Does this mean that some of the government establishments are going to assist the
universities financial activities?

Laughter

Spicer: We should point out that Jean-Pierre collaborates quite a bit with ...

Kotidis: I wanted to make a point in the definition of industry. I think we keep calling industry "everybody who is not government or university." That's not true. Industry is the end user; that's one aspect of it. But also it's the champion that would take it to the end user. That is also industry, and that is, I think, the missing link because I heard applications. Everybody has mentioned applications, and there is work in government, there is work in university, but there is no one to make this transition, and that's what I meant by my earlier comments on a champion.
It's not the end user; it's the someone who will take it to the end user.

Spicer: Maybe we should jump down to the last bullet here on the screen in terms of checking into who should be the producers, consumers, marketers of the technology. Jim has a rather lengthy question associated with this. "Do you envision that laser ultrasonics will be more likely supplied to end users who will purchase the equipment for their own use or will it be made available through testing service providers?" I think this addresses some of the issues that were raised earlier with regard to "if you have to make this initial investment in order to get into the game to see whether or not it is a useful technology," what role do you see people playing in the future in terms of developing the technology and spreading the technology? Will it be a few isolated centers where people would have to go there to assess whether or not the technology is good for their application? Or will it be that they can buy a $ 1 0,000 box and try to do the work on their own? Any thoughts on that?

Dunning: Industries that we've been interacting with basically want a turn-key system where their person on the factory floor does not have to understand what's

in the box and can operate this very simply and safely. This is what we have run into, and I think- this is very real when you start talking to the end users.

Spicer: That they want just a box they can buy instead of a testing service?

Dunning: There is a whole industry out there where they recommend testing services to come in, in the petroleum industry. That's the way that they operate, on their tubes and processing facilities. But, in general, they like to see full, full-blown systems.

McKie: I think some of the niche applications that people are pursuing are so diverse. I don't see how any one single source, testing facility, would serve the needs of the whole community. That would be very difficult to do, and most of our customers certainly would want to have a system installed in their facility.

Spicer: But isn't that after coming to you and asking you to look at something? For example, at this conference you presented some nice work on ???, but after, they came to you and asked you about the technology.

Dewhurst: That's right. There are certain things that we are capable of doing with the
laboratory system. The testing house may not have the same flexibility that we have now.

Lisa Zellen: Lisa Zellen. This is a real opportunity for you to put together a catalog for new LU users. Put together your name, your address, what you have available so that if Andy McKie doesn't have what I need, he says go to this other person. I put my sample in the mail, it goes to that other person. The test is done, the results come back, so that 1, the end user, have to go through a minimum of effort to find the facilities that I need. As an end user, going back to the question that was stated by Dr. Wagner, if you can build me a laser-based ultrasonic box for $10,000 ...

Laughter in the room

Zellen:... then I'll buy three or four of them. But the estimates I have heard are a lot more
than that. O.K. So I cannot justify going to my management with, say, anything over than $150K, if there is someone outside of my facility who has a black box and is doing this, say, for the petroleum industry. I have to go to their facility and say, would you do this inspection for us. So I need resources in a catalog, I need prices for systems in the catalog, and let's get it together.

Spicer: Well said.

Laughter in the room. Remark by another panelist accompanied by more laughter.

Kotidis: O.K. We at Textron routinely do this. That is, every time we have an application, we always ask the customer to send us a sample. We always respond with a set of data, then we have what we call application engineers, where the evaluation is done whether it makes sense in a real installation to proceed. The two examples that I gave you were cases where we decided to go ahead. But we've done hundreds of samples that people have sent and said it would not work, it might work in the laboratory, but it would not work in your environment. So, we do this routinely, and I'm really surprised with the question because this is standard. Most people do that. It's a new technology; it's expected by the customers really.

Spicer: I agree.

Robert Green: Unfortunately, I am sorry to say that this does not go on. Most people don't do that. Most of them lie.

Laughter

Green: I'm really telling you the truth. I used to do some work on acoustic emission, and many of you may have also. It was always sold by over-zealous salesmen. It didn't do the job that people expected it to. And now it's slowly coming back around. The same thing happened in ultrasonics. I ask guys older than me, “Did anything happen like that before?" They said, "Yes, ultrasonics." There are still some guys alive ...

Kotidis: By the way, that's the hardest thing to do. It was the hardest thing to say, "No."

Spicer: Thank you. Anybody else have a comment?

Drake: I'd like to comment on the expectation and cost issues. I had a phone conversation one day telling them we were doing it ten times faster than we used to do something. This person did the same basic application and said, "Sounds pretty good. How much does this cost?" I said, "Well, these are going to be million dollar plus systems." He said, "A hundred thousand buck s is a lot." Then I said, “The machine you just bought was $2-1/2 million dollars to solve this problem," but for some reason, because it was laser ultrasonics expectation was that it should be 10 times faster and 1/10th the cost. And I'm not sure why that expectation's there; a bit unfair. So let's try to go 10 times faster first, and then we'll get it cheaper also.

Spicer: Stuart, in your application on beverage cans, I think that's kind of unique in that you're in a university and you've seen this all the way through to

where you can give testimony for it. What was that experience when somebody comes to you with a problem and you get sucked in and follow it through? How did that happen?

Palmer: We decided in the university to set somebody a task for a year and employ somebody for a year to go out into industry, explaining the technology that we have, the technology of noncontact ultrasound, we don't mention laser, we don't mention EMAT, just noncontact ultrasound, and do you have problems that we can solve by noncontact ultrasound. And resulting from that, we had a whole range, of course, of weird and wacky suggestions. And some of them bore fruit. All of them bar two resulted in applications where we used solely EMAT's because they were metal and because the temperature was only probably 500°C or 600°C. So we have applications in electricity generating industry, we have applications in the galvanizing industry, that we can solve with EMAT's. The only two that came through where we used laser-based systems was this one, the one I described yesterday in the canning industry, with a little small company that had never heard of laser ultrasound. And the second one was measuring the thickness of plastic sheet, plastic film that was being made. There we had developed a laser system, laser generation, and a laser beam deflection system for detection, very cheap laser detection system. We demonstrated it in the plant, plastic plant, and described it at QNDE about three years ago. Sadly, the cost of a system that we proposed to them was L40,000, $60,000, but they described that to the company who provided a new gamma ray system, and the gamma ray price came tumbling down, and we lost our collaboration with the plastics industry. So, that's the other thing, you know, to always bear in mind, and I'm sure you all realize it. If there is an existing solution out there and you think you're providing a better solution, watch out because the existing solution will either improve or become cheaper or whatever. In short, you don't get the business.

Laughter.

Palmer: And the standard one I always quote is this transformer core, which is not really in this conference at all, but silicon iron has been the standard transformer core material for years and years, but there have been people proposing for the last 30 years that amorphous materials will take over tomorrow. But tomorrow never comes. Silicon iron ores gets better and better, just enough better to keep the transformer people out of business.

Sachse: I'd like to echo that. I teach a course at Cornell on a compact disc player. And it's very informative, very instructive, to look at how this compact disc player took over completely from the phonograph record just 10 years ago. The first CD player for commercial use cost about $1,200. Last week, I could buy a CD player in Ithaca, NY for $37.97.

Spicer: And free from Time Magazine.

Laughter.

Dewhurst: What are the reasons? Is that it became a standardized product?

Sachse: But it also had tremendous advantages over the phonograph record.

Dewhurst: Yes. Well, we're trying to say that laser ultrasonics has tremendous advantages, that it's truly noncontact, and very few, well, there is no other ultrasonic system which is noncontact.

Sachse: But the dynamic range is not as good as the conventional.

Spicer: What niche applications are there to support what you just said?

Dewhurst: Well, the composite industry is one.

Spicer: That's one. How many others are there?

Dewhurst: I don't know.

Spicer: Monitoring microstructure in hot steel.

Dewhurst: Yeah.

Spicer: Rigid ...?

Lorraine: Peter Lorraine from General Electric. We think that there are many other applications where laser ultrasonics is beneficial. GE is a multi-million company with many expensive products we manufacture. We don't manufacture laser ultrasonic equipment; none of our customers require laser ultrasonic equipment. But when they require measurements that can't be made any other way, if we make a $100 million gas driven power plant, 1% in efficiency buys us $10 million in profit. To get that performance, we need a thermal barrier coating with certain performance, to get that performance on TBC we need laser ultrasonics. So in very expensive markets, we can find process niche applications where we put this on and make a difference. Similarly, NDE is a very expensive business for us for our aircraft engines. There is a conservative number. That is, if we can do something that reduces our cost and brings us new capabilities, it is very interesting to us.

Dewhurst: Yes. What we need are some standardized products that we can handle some of

those problems with.

Lorraine: I think that's true, but there is a diversity of applications within our company. There are some that become niche technology that are developed for corporate research where we make one of and it goes to a vendor, and then, as an example that our company has several hundred people working in nondestructive testing, our aircraft engine business uses standardized, semi-standardized equipment that are bought for vendors and used on a broad scale. So there's a host of applications for both, one of and standards. In our company, we want to have a lot of standard ones, anything that reduces cost will help us. But the single greatest thing right now is non-recoverable engineering costs, transitioning to isolated applications. We derive benefit, at General Electric, because we have enough customers, we think we can pay these costs once and serve multiple businesses within our company.

Spicer: Would anybody else like to comment on this?

Rauschford: I'm Paul Rauschford from Potomac Energy of Canada. One of the questions I'd like to know is, "What is the major cost of laser ultrasonics?" What component? Is it integration or is it the individual, is it the Fabry-Perot detection system or is it the laser system? I don't know. And if Fabry-Perot is the most expensive, it's probably the one to drive down.

Several overlapping comments.

Monchalin: All the elements of the system contribute to the cost; Fabry-Perot demodulator detection lasers, generation laser, naturally some mechanics if you want to scan, computer system software. In a system for inspecting composite material where you want to do fast gauging, software is not a small cost, computer storage. And a lot of people have been talking about costs of the demodulator system. Actually, the cost of the demodulation system is quite small. So, it depends on the application; its a niche technology, so in one application the cost of one laser may be significant while the cost of the demodulator insignificant.

Drake: Those are the exact same comments, it son of depends on the application. If you want speed, which is what we want, it takes a lot of resources. Every aspect of the system is driven to the absolute limit of what's available. That's one of the areas where the government, if you want to go fast, you're going to spend a lot of money just on the laser technology. And how do you go faster? How can you do all these things? I can't personally drive the laser market. They match very large markets, especially telecommunications. It's very difficult for me to go to the laser vendor and say, "Gee, I want one of these." A million dollars might not get close to those guys talking to me. Ten million dollars might. So these are the kind of dollars it takes sometimes to fundamentally change the laser vendor's mind,

because I can't tell them I'm going to buy a hundred or a thousand, which is what they want to hear.

Spicer: Would you like to comment on cost, Andy? -

McKie: Yeah. These are valid comments. As far as putting together an industrial laser system that, from my experience in setting up a system in our lab, by far the greatest cost has gone into our probe laser if you want to look at materials that are black, you know, very poor reflectors, because of dumping enormous amount of energy on that target just to get enough light back to make any detection at all. And, you know, we're looking at $160,000 just for a probe laser. And that dominates; in our case, that dominates the cost of the system.

???: I was going to say that in starting to look at niche markets, instead of trying to build one system that works everywhere and it costs XX dollars which You can blanch at, you stop to look at the particular niche in ways and cut back where you can in the system. This is similar to what you were saying in your talk today. You don't try to have everything over specified or some things ten times more than what you need. You try to tailor, and then you can bring the cost down, I believe, with regard to that. If you only need to pulse a laser once a second, why get a laser to pulse 100 times a second?

Spicer: Would it be fair to say that once you try to do imaging, as in C-scanning, the costs go up tremendously?

McKie: Absolutely.

Drake: In our case, we do have to over specify.. I don't want to follow acoustic emissions past in terms of putting something out there where somebody will be disappointed in its performance. So that means in certain situations, I have to have 100 times more laser power than I have to have in other situations. I have to provide that 100 x, and I have to have the dynamic range to do the worst part that they give to me. So my cost is actually in the worse case scenario, which may only be 5% of the problem, but we have to solve that 5%.

Overlapping comments.

???: There may be other needs where a person is only wanting to look at something that's fairly small so they don't have to have any tremendous scanning capability. Perhaps the speeds are such that they don't need ..., or they may have a lot of them. So that system is totally dedicated to that.

Drake: We're working on research structures where we can lower these costs. In Andy's example with dark composites, it's more than just dark. Sometimes they are real shiny, which is actually much worse.

???: When we're hitting a surface at 65', it takes a lot of power, but what can we do?

Mixed comments.

Spicer: It's kind of a paradox that the shinier your surface, the more difficult it is.

Drake: ...and then I have to have the dynamic range for when it comes on axis. It's extraordinarily bright, so it's the worst of all worlds.

Spicer: In too many talks, people say, "Well, we painted it," but you don't know whether it was too shiny or it was too dark.

Drake: See, I don't get to do that.

Spicer: Any other comments? I think what I'd like to do is open up the floor to some questions perhaps.

Delano: I'd like to comment on just what's been talked about. Lisa Delano from Boeing North American. If you can build me a laser-based ultrasonic system that interfaces to the ultrasonic detector that I already have, the Test-Pro system the Krautkramer-Branson system, to the mechanical system that I already have which may move the part. Now, you've just reduced the software costs, the hardware costs, and the cost of the ultrasonic system, completely out of the system. All you have to worry about presenting to me is a box that the interferometer and the laser is in. Would that be so hard?

Loud laughter. Comments.

Monchalin: It's no problem to do that. No problem because the signal we get is an ultrasonic signal, except if you have an old system which is analog. Generally, we want to do digital acquisition and do some signal processing.

Delano: We (Boeing) are there already.

Monchalin: If you are there, it should be no problem. And I'm sure they want business retro fitting and getting additional options besides conventional ultrasonic inspections.

Kotidis: I wanted to comment on that question. Why should we do that? I'll tell you why. The question is, yes, maybe we can do it with the..., but is there a big market? Maybe there is. If there is, then it makes sense. And is it something like the system that Tommy has, which is a very powerful system that do the job? If yes, then you have to prepare the ... benefits, and all that, the size of the market. Nobody wants to lose money, so the point is that when you ask the question, "Can this be done for $ 10,000?", you have to always ask the question "Why?," and "Who?," and "What are the requirements?", and "What's the future of the market?," "What's the size of the market?," "Who's going to service it?," "Who's going to warrant it?" I don't believe these questions have been asked. These are very serious questions, so that's my point, and I think we should look at the bigger picture. And I want to conclude by saying some industries have done a technology road map. It's been done in some other industries and basically it is a panel of experts sitting down and saying we have these needs, we have satisfied these needs, we're probably going that way, and that's what we need for that. It could be that your application ...

End of tape. New tape.

Spicer: Curtis, would you like to comment on that, in terms of forming a road map and what the Air Force sees for the future of this?

Fiedler: First of all, the Air Force has road maps for everything.

Laughter

Fiedler: They have seen my road map in laser-based ultrasound and where we're going there. Our road maps are directed primarily at the problem of aging aircraft. In the future, that's the thing that's driving us, that we can sell to our customers. Our road maps are driven by: How (do) you inspect a lot of airplanes very rapidly? For corrosion or fatigue? For other problems? It works. With the road maps we can explain to our management why it makes sense to invest in this technology.

Spicer: Would anybody like to add to that?

Someone from Federal Highway: One of the problem that our cracks. My question is, historically, ... there's no contact or to use the laser-based ultrasonic method. What other advantage for using this technology over the conventional ultrasound?

Monchalin: Laser ultrasonics has some advantage for surface wave generation. It is quite easy to generate a surface wave and fairly efficient. There are also tricks where you could increase the amplitude of the surface wave by sweeping the beam or sweeping gratings. Since you are talking about crack detection, generally you could detect cracks with the surface wave and laser ultrasonics, in this case, would be a technological advantage. Plus, you could generate on comers and a curved surface, so I think that's the answer to the question.

Federal Highway person: How is the distance? For example, if I want to inspect a bridge and there's some area that I can't reach, how far away can I be?

Monchalin: In principle, you could be far away but probably to talk about a very expensive system with a very big laser and very big receiver aperture. But what seems to be rather reasonable is you have some portable movable system which is operated by a person and... This is not perfection, but the person could look at cracks in different geometry and curve surface which would be very difficult to find with conventional ultrasonics.

Dewhurst: We shouldn't overlook the fact that in our mission to remain non-contacting, compared to conventional transducer systems, the spatial extent of the generator and the receiver is smaller. In general terms, we're going to get better defined information, time-of-flight, out of the system. That might-help. In fact, there have been demonstrations of time-of-flight diffraction techniques, looking at cracks, noncontact, as well as the... technique that's been used for many years for sizing surface breaking cracks.

McIntyre: A lot of... components are very important and I've heard those touched on several times and there may be two other items that may be more critical for really opening up the market which may be what it really takes to accelerate the development of this technology, and they might be raw functionality. What I mean by that is, if you put a system in a plant that would measure thickness, material or mechanical properties.... and temperature all at the same time, and do it in real time where it can be used as a process control tool, that would create a large market in those seven industries that I shared because those folks, as you heard before, produce millions of tons of material like paper, glass, steel, aluminum, metal-cast parts, pharmaceuticals, chemicals, etc. Real-time process control is critical for them. If they can measure something correct the process and save them millions of dollars, sometimes a day, to the extent that this can be used as a process control.

Spicer: Of any commodity material that would be true. Does anybody want to comment on what the potential for solving all those problems in terms of gauging thickness, getting temperature, ... all at once. Is that something that would be foreseeable for the future?

Drake: I've got a great story about potential. This is from a University of Texas football coach. He was describing a young athlete, and the word "potential" was used for him. The coach said, "That just means he ain't done it yet." That's kind of where we are with some of this stuff the potential is, someone just hasn't done it yet. Somebody should go out there and do it. I know Jean-Pierre has done it. Let's see what he thinks, temperature, measurement, characterization.

Spicer: How many of those can you do simultaneously?

Monchalin: Well, I think that this is possible. We have done temperature measurement with surface waves. We could have a laser ultrasonic system configured to generate surface waves. With the bulk wave we could measure thickness. ... Actually, it's supported by DoD. There is a program to have multi-function, multi-phase sensor based on laser ultrasonics and, of course, the sensor would give significant feedback to industry to justify the sensor which is very costly.

Spicer: Would anyone else like to comment?

Member of Audience: Actually, I'd like to follow up and ask the question. You mentioned that the surface waves may be an advantage when using the laser. Correct me if I'm wrong, How about looking for internal cracks. Is there still an advantage?

Monchalin: I don't know that we have a research approach because you generally have to send wave at an angle which is done quite easily using a wedge and conventional ultrasonics. With laser ultrasonics you have to shear the waves, use a grating. This has been done in research, but that makes the system more complex and more costly.

Comment from the floor; unable to decipher.

Monchalin: Could not decipher his comments at this point.

Spicer: We had a question or comment right here?

Jeff Doman: Oh, yes. I wanted to address some of the things you were saying from Boeing, to go back to that question. You asked if we could replace your traditional ultrasound, your traditional detection system. If we could do all these things for process control, make all these sensors for process control, would we then really have a market of industry that's asking, "Gee, could you replace our current sensors and make them better?" With those added input that you're giving to the process, would the controllers even know what to do with it? I mean, do we have a tremendous resistance in the market due to the fact that if we supply all this

information, will the market be accepting? Does it know what to do with this, and would they be willing to invest in it?

Spicer: Would you identify yourself, please?

Doman: Oh, I'm sorry. Jeff Doman, Textron.

Devlan (Boeing): I have an answer. I'm Lisa Devlan from Boeing North America. I have been given a part from the engineering side of the house that I cannot inspect. And yet, they're going to go ahead and build this part, and they're going to build 110 of them over 2 years. I've got to come up with a way of inspecting them. OK. Laser ultrasonics has already been demonstrated to be successful. Now I need a price, and I need a black box.

Spicer: Sounds like you need to get together with Andy.

Laughter.

Lorraine: Peter Lorraine from General Electric. Regarding the use of process control data, the case is made. People who are our customers are materials scientists who design sophisticated multi-phase engine alloys who care about microstructure. We believe our competitors care about the same things. If in-process we can measure microstructure, we can save throwing away $400K parts. We don't have to have a huge impact on ... before the economic case is made. So these are niche ... We don't need to know temperature. We know temperature of our part. We want to know microstructure. Someone else may want to know something else. But the case is there, and the arguments made to ....

Spicer: This isn't really commodity material, and I think ... issue out there.

Lorraine: We make tons of this stuff. .

Spicer: I know. I know.

Lorraine: We build $100 million factories to make this.

Spicer: This can't compare to modern materials though. It isn't a commodities market.
Gil, did you have a comment to make?

Dunning: There's one advantage to laser-based ultrasound that hasn't been touched on, and that's the fact that you can have fiber optic delivery and reception so that you can multiplex between many different stands and get good information simultaneously. Or you could leave the fibers in place and do characterizations over

a long time period at the same locations if you're measuring for corrosion or coke buildup or something like that. And there would be markets that we could capitalize on, on this aspect of laser-based ultrasound.

Michael Ehrlich: Michael Ehrlich, Johns Hopkins University. I just have one comment to make in answer to your question. Jean-Pierre was talking about surface breaking cracks. Now you're talking about internal cracks, and, I assume, also surface breaking but from the side we can no longer see,--from the back surface. Typically in conventional ultrasonics, you would test things like that with angled shear waves. In almost all the talks we've seen and all the utility that we have up here, we're always talking about longitudinal waves being transmitted to the material. In the thermoelastic generation case for a surface source, you get excellent shear wave generation, excellent angled shear wave generation. So there is another mode of sound that we do have available to us to do this sort of inspection. We've done some work using that. The difficulty with the shear waves is that on the detection side, they do not manifest themselves well in surface displacement. So they become difficult to see. One way to get around that, that we've worked on, similar to Stuart's solution here, is couple a laser generation technique with an EMAT reception. And you can do that very well actually.

Spicer: That doesn't hold very well on composite parts....Believe me. This is a unique opportunity. You'll never see this collection of gentlemen at a conference sitting still for so long. If anyone can care to ask a question of the panelists ...

Jorge Alcoz (Karta Technology): I'd like to comment that it seems to me that laser ultrasonic technology has been driven by the aerospace industry... so these are biased to the inspection problem. That is a bad problem. You have to have very fast acquisition. Now process control, many times you have more time so you can average. For those the sensitivity problem is not that big. You can average 1,000 times, maybe 10,000 times, and get your noise level down a lot. More ...

Spicer: In some applications, absolutely.

McKie: Andy McKie. That's a very good comment. I think, you kick this ball around cost. You know, it's been kicked around for many years and really I think you can split your applications into two specific categories scanning categories where you need rapid inspection and scanning the laser beams, and those are generally going to be more expensive systems and you're going to have more stringent requirements. But these, certainly these in-situ process monitoring applications where you may be monitoring a single point, we can really do a lot of work to reduce the cost and get a very user-friendly small and robust system for these types of applications. So I think we need to make sure we don't get confused and clearly delineate these different applications.

Klein: Marvin Klein from Lasson Technology. I want to throw out a little ringer to remind people that there is another option for noncontact ultrasound, and that's air-coupled ultrasound. That may not work for process control where you have, for example, hot parts. But you do have a stand-off on the order of 5 cm, give or take, and for applications where the part can't stand water, using a squirter or bubbler immersion, for example, it's surprising how many of these composite parts can be measured pretty well with air-coupled ultrasound. You can also get resolutions down to a millimeter with focused transducers. So I'm not trying to sabotage what
we're doing here but... also need ...

Spicer: I think Bob Green can comment on this.

Green: I wish you a lot of luck.

Laughter.

Sachse: Since you opened it up, why not use a spark? All you need is a spark plug and a capacitor discharge system for $19.95 at Radio Shack.

Spicer: How close do you need to be to the sample then?

Sachse: You can spark right to a sample if you like.

Spicer: If it's not a composite.

Green: I don't think you ought to digress in

Spicer: No. I don't think so either.

Green: ...publish all other systems...

???: ... I do think that is a good point that, you know, people in industry are starting to get interested. The news is getting out so they call me about it. They say, "Can you solve our problem?" We looked at it and said, "Yeah, we can solve your problem." Now, as engineers, we might know of other much similar ways to do it. There may be that temptation to really try to press ultrasound. O.K. So in part in telling the truth that, you have to, you know, in its full..... because if we invest a lot of money in putting knowledge out, in having ultrasound solve their problem and then, you know, they think about it for a little while and all of a sudden decide a spark plug will do just fine, now, then the, you know, you get a bad impression and we all lose money.

Spicer: You still have those niche applications, and I think laser ultrasonics is unique in its ability to perform at large stand-off distances, unquestionably. There is no other technique that allows you to do these things.

Klein: Those are the problems you should solve.

Comments in background by various persons; could not decipher.

Spicer: Would anyone like to comment? Any questions? I'd like to thank our panelists. I urge the audience to come up and ask more questions. I found it a very interesting discussion, and there are still questions I have for these gentlemen.

Monchalin: There is something additional. This is not in a question, but should before leaving. ... lead to such a meeting between laser community.

Spicer: I think this is one of the first times when we got the concentration of people who've been around for such a long time in laser ultrasonics..., and I think it's something that we should continue, and I know that's something Jean-Pierre has had in mind, to identify a forum in which people who actively pursue laser ultrasonic research and applications can continue to have this type of interaction. Is that a fair statement?

Comments; laughter in room.

???: I just suggest you don't start a new journal.

Laughter.

Spicer: Let's thank our panelists.

Applause.

Spicer: Thank you very much for coming.